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Environmental Security

Resilience of Cities to Terrorist and other Threats

Learning from 9/11 and further Research Issues

Edited by
Hans Pasman
Igor A. Kirillov

Springer

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Resilience of Cities to Terrorist and other Threats

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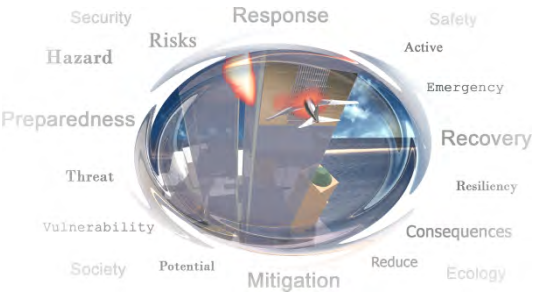

Resilience of Cities to Terrorist and other Threats

Learning from 9/11 and further Research Issues

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PREFACE

1. Background and Objectives

The contents of this book are based on information brought together in a NATO Advanced Research Workshop held in Moscow, Russian Federation from 16–18 July, 2007. The workshop was instigated by the 9/11 events in New York City and was entitled Urban Structures Resilience Urban under Multi-Hazard Threats: Lessons of 9/11 and Research Issues for Future Work. It had as a sub-title: How do we make our cities less vulnerable?

The loss of life as a result of the collapse of the WTC towers in addition to fatalities as a direct result of the aircraft impact and crash, forces one to consider possibilities of improved mitigation measures. This need is amplified by the erection of office towers in large cities all over the world as well by the multiple use of space in the development of traffic nodes in urban centres in which office complexes, shopping malls, apartment buildings are merged with underground or overhead highways, parking garages, sport facilities, metro, train lines, and station buildings. This all adds to the increasing complexity of our society. Terror can be relatively easy sawn by planting explosives or other means if not adequate measures are being taken. By natural disaster panic can result in unnecessary additional death toll. The objectives of the workshop have therefore been:

- To raise awareness for the countering of natural, industrial and terrorist threats by development of more resilient systems
- To stimulate discussion on "combined-hazard-resistant urban structure" as one of the key elements of "inherently secure and resilient city"
- To review the "state-of-the-art" in the post-9/11 topical applications—structural integrity of urban structures, fire resistance of structures, structural materials, active fire protection, building evacuation, emergency response, planning procedures and practices, education and training
- To define the "knowledge gaps" in understanding characterization of combined hazards, of which the effect on its own is known but

the synergism is not, in advancing protective engineering and attempting to quantify risk for the purpose of prioritising measures and cost-benefit studies

- To encourage development of engineering a "resilient city" concept, taking explicitly into account a terrorism threat
- To facilitate information sharing and research coordination.

2. Clustering of the Contributions

The contributions to the workshop have been quite diverse but in agreement with the multi-disciplinary nature of the problem field. To retain an overview the papers have been grouped as follows:

2.1. NATURE AND EFFECTS OF POSSIBLE THREATS

Janzon and Forsen present a wide overview of present day city vulnerabilities and terroristic threats by ballistic weapons, explosives, fuel-air mixtures, chemicals, and electro-magnetic, nuclear/radiological and biological means. They also describe briefly measures of mitigation of consequences. The paper of *Maschio and Milazzo* contains a risk analysis case study of a transportation route of hazardous materials through a city with also a terroristic threat in mind. *Filip and Demnerova* describe possible bacteria and virus contaminations in groundwater being a source for drinking water, *Batista and Martins* treat a case of radio-active contamination of the soil and how this can be monitored on country wide scale.

2.2. FIRE AND COLLAPSE RISKS OF URBAN STRUCTURES

Quintiere analyses the collapse of the WTC buildings by posing critical questions about the findings of the investigations by the U.S. National Institute of Standards and Technology and describes some own scaled down, floor fire experiment. *Mlakar et al.* describe the behavior of the structure and collapse of the wing of the Pentagon building by aircraft impact and fire load. They focus on details of columns and girders. *Shebeko et al.* perform a fire risk analysis on multi-fuel tank stations with compressed fuels such as LPG and CNG

and calculates individual risk contours and group risk. *Panteleev* tackles the risk analysis approach of a high-rise building, develops a generalized model and derives a simple application inspired by the WTC buildings case. It shows the problems a risk analyst is confronted with.

2.3. MATERIAL PROPERTIES, STRUCTURAL DESIGN AND TESTING

Banthia describes the improvements that can be made with respect to impact and blast loads applying new composite reinforced concrete in structures. *Kodur* focuses on the improvement of resilience high performance materials can offer but deplores their resistance against fire. He makes a plea for better fire safe design and corresponding research. *Weerheijm et al.* analyze the blast resistance of slabs in view of reducing risk of collapse of structures by explosion loading and calls for international cooperation to solve the problems. *Roytman and Lukashevich* introduce a simplified engineering method to quickly (promptly) determine the effects of combined hazards by massive impact (aircraft), possible explosion and fire. Subsequently a Virtual Reality approach is applied to obtain an instant overview and adapt parameter values.

2.4. FUTURE STRATEGIES AND PLANNING

Krauthammer et al. outline a plan for multi-national research efforts and a strategic research agenda. They further consider the necessary research thrusts to enable an integrated risk assessment approach with a very wide scope including socio-economic aspects. *Fleischhauer* considers what is necessary in urban area planning in view of a wide variety of accidental and intentional threats. He further analyses results of planning procedures in the various European countries and considers the deficiencies showing up in the case of the Elbe flooding of Dresden in 2002.

2.5. WARNING SYSTEMS

De Stefano and Matta introduce the concept of (health) monitoring of structures with distributed sensors for the purpose of safety and security.

They treat extensively the signal processing required to derive from the primary signals at a meaningful indication of damage symptoms for structural health monitoring before collapse will take place. *Kulchin and Vitrik* offer a few new concepts of opto-electronic sensors in a fibre-optic network and neural network filters to monitor displacements.

2.6. EMERGENCY RESPONSE PLANNING

To optimise emergency response force capacity for calamities given various risk sources in a region *Van der Torn and Pasman* explain the problems encountered in optimising emergency response and the possible approaches when performing land use planning and design of structures taking into account results of risk assessment This is a multi-faceted problem to tackle for which new modelling (scenario analysis) and (injury) data have to be generated. *Kisa and Jelemensky* describe the use of computational fluid dynamic modelling in predicting toxic or explosive (heavy gas) cloud dispersion and compare code results with experiment. *Galatas* presents an overview of medical countermeasures that can be taken after an attack with chemical or biological agents, or radiation/nuclear devices. The paper describes medical management measures and provides guidelines, also based on the experience with the Greek 2004 Olympic Games. *Kholshevnikov and Samochin* describe fundamental work on modelling evacuation rates as a function of person density, emotional state and required manoeuvres of 'flow of people'. This includes detailed observations of actual large scale experiments including determination of statistical fluctuations. *Charvat et al.* developed a so-called spatial data information system which on the basis of distributed sensors, a geographical information system and other data systems can help out in emergency management. This is described in quite some technological detail. *Danilicheva et al.* review the benefits and problems of virtual environment systems application during the emergency prevention, preparedness, response and recovery phases. *Wybo*, last but certainly not least focuses on the human element and describes how simulation and information can help to determine and improve the robustness and resilience of organisations when faced with disaster. Preparedness of the mind is of utmost importance.

Acknowledgements

We wish to thank the NATO Science for Peace and Security Committee in particular the NATO-Russia scientific cooperation for their support to grant the Advanced Research Workshop enabling us to bring together the contributors from various parts of the world, who in the exchange of views and discussion made the synergy. In this connection we express sincere acknowledgements to Dr. Fausto Pedrazzini, Programme Director of the NATO Public Diplomacy Division, for his support. We appreciate deeply a long-term support of the safety and risk analysis related research studies by the Russian Foundation of Basic Research. We rate highly an opportunity to be the colleagues of and to learn from Prof. Sergei A. Tsyganov. Also we are indebted to all contributors for their effort to write it all down. We are really thankful to Olga Frolova, of Torus Press Ltd. for her valuable assistance throughout the production of this book. We extend our thanks to Wil Bruins, Springer Publishing Editor, for her help and recommendations. Special thanks to Igor Lukashevich, Kintech Ltd. for collages and fruitful long-term cooperation. Last but not least, we are thankful for life to Ineke and Natasha for their resilience and inspiration.

Hans J. Pasman

Igor A. Kirillov

THEME 1

NATURE AND EFFECTS OF POSSIBLE THREAT

Collage by Igor Lukashevich

THREATS FROM TERRORIST AND CRIMINAL ACTIVITY AND RISK OF DANGEROUS ACCIDENTS—RESISTANCE AND VULNERABILITY OF THE URBAN ENVIRONMENT AND WAYS OF MITIGATION

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Abstract: In modern society, the appearance of many regional conflicts and the vastly improved communications, both by air transport and via the Internet, have meant that organized crime and international terrorism have been proliferating rapidly over the world. Similar events that occur daily in Iraq and the Middle East rapidly spread and occur in most European and other nations, be it at smaller scale. Also, the number of natural and man-induced disasters is increasing. Modern society's increasingly complex structure makes it more vulnerable than the local society prevailing up to mid-1900s. Although the great majority of human casualties are still caused by accidents and disasters, violence applied by organized crime and terrorism and ways to prevent, protect against, pursue perpetrators, and respond to such acts merit special attention. The paper describes some of the principle ways and means of attack in urban scenarios by terrorists and other criminals, their effects, and points to some ways to protect society and mitigate consequences.

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Keywords: organized crime; terrorism; armed attack; bombings; weapons; explosives; blast; effects; glass windows; protection; mitigation

1. Introduction

Modern society is characterized by increasing urbanization. Even in peacetime, many threats and risks exist that can affect persons, residential, business, and official buildings and other infrastructure adversely. Some of these are listed below. The focus here will be on acts of terrorism and ways of protection and mitigation.

Terrorism is based on inspiring fear among citizens. If this can be avoided, the efforts of terrorists will be in vain. This can be achieved by attitudes, beliefs, and psychological resistance among the population. Building a society that is less vulnerable to criminal violent acts, which will serve to limit and mitigate the effects will also be an important way of reducing the degree of public fear. It will, indeed, be a formidable task, since terrorists will seek to aim against the targets of highest vulnerability that potentially give the greatest effects.

The lists of threats and destructive means and methods below may seem overwhelming. Yet, the purpose of this review is to enable society to find means of counteraction, protection, and mitigation of effects. Both "normal" crime and terrorism are societal problems that have to be solved by other than technological means, such as political, social, and legal efforts. Technology may, however, offer some solutions to avoid some of the worst consequences of illegal violent action of different kinds. Especially, society should be made aware of the hazards existing and some quite effective measures that can be implemented at no great additional cost, in particular, when planning, building, or retrofitting buildings and facilities that may run risk of being exposed to such actions.

If a path to the better there be, it begins with a full look at the worst!
Thomas Hardy

2. Worldwide Society Development

2.1. COMMON TRENDS

We have all noticed a rapid development of our societies and the conditions for their existence. Some typical developments are:

- Strong knowledge and technology development and use
- More power to the "Market," less to governments and authorities
- Globalization, relocalization, outsourcing
- Increased dependence on transport and flows of goods and persons and
- Increased complexity of critical infrastructures.

2.2. SOCIETY'S NEW VULNERABILITY

There have been pronounced changes in many nations, especially, the western ones, from being groupings of many local, relatively self-sufficient societies, into much larger interwoven urbanizations and conglomerates, jointly dependent on infrastructures and systems of ever increasing complexity. Also because of the much increased market influence, nobody has the full overview and responsibility for the entire system of society and its problems.

There exist very strong increases in:

- Dependence on information technologies (IT) and communications
- Vulnerability to computer and network break-downs
- Mutual dependencies between functions and systems
- New types of warfare, sabotage, terrorism, organized crime and
- New weapons technologies, proliferation of weapons of mass destruction, and the marked emergence of a grey zone between war and peace.

2.2.1. *The Complex Society*

The following infrastructure systems are often mentioned as most critical for society's normal function and the survival of the population (Eriksson and Barck-Holst, 2005):

- Electric power grids
- Electronic communication
- Water and sewage
- Transport systems and
- Financial systems.

Mutual dependencies between these systems can lead to potentially much increased vulnerability.

2.2.2. *Power Supply*

Modern society, and, in particular, the urban one, is extremely dependent on energy supply. An important part of this consists of electricity. In general, society (at least, in Sweden) will not be considerably damaged by a power outage of less than 6 hours' duration (Frost *et al*., 2004).

- The 6-hour limit is generally the highest acceptable one for health and medical care, community technical services, and mobile telephony.
- Emergency wards and local medical care units as well as households can generally endure up to 24 hours.
- Telecom and command and control systems usually withstand up to 2–3 days, depending on time of the year and geographical coverage of the power outage. This is also valid for police and security services, rescue services, transports and fuel supply, bank and finance systems, agriculture and animal farming, food supply and certain industrial activities.
- If spread is less than national or regional, some services can be maintained for up to one or even a few weeks without mains power supply.

2.2.3. *Example: The Black-Out in Italy on 28 September 2003 (UCTE Interim Report, 2003)*

This remarkable sequence of events was triggered by a trip of the Swiss 380-kV line at 03:01 caused by a simple tree flashover along the line. Other lines took over its load, as is normal in similar situations ("an $N - 1$ situation"). Due to this, the other Swiss 380-kV line, the "San Bernardino" line, was overloaded. This was acceptable for about 15 minutes in such emergency circumstances, according to operational standards.

At 03:11, by a phone call, Italy was asked to reduce imports by the 300 MW with which Italy exceeded the previously agreed schedule. That reduction was in effect at 03:21. This measure was, however, insufficient to alleviate the overloads. Another line soon also tripped

after another tree flashover, probably triggered by the sag in that line caused by overheating of the conductors.

Having lost two important lines ("*N* – 2 situation"), the overloads on the remaining lines in the area became intolerable. Consequently, the Italian Power System was isolated from the rest of Europe. But during the high overloads, instability phenomena had arisen in the affected area. The result was a very low system voltage in northern Italy, which, in turn, caused emergency shut-down of 21 out of 50 large thermal generation plants in Italy.

Notwithstanding countermeasures it proved impossible for the Italian system to operate separately from the UCTE network. About 2½ minutes after the disconnection of the nation, the blackout was an unavoidable fact.

So, in fact, a simple tree flashover caused a major European nation to be "shut down." It took up to 19½ hours to reconnect all Italian customers to power, with Sicily being last! In other circumstances, and especially if the power transmission infrastructure is damaged and the blackout has longer duration, power generation plants and transmission nodes may have to be manually restarted and re-connected. There are usually few people available with the competence to do this work, so loss of electricity may indeed prevail for months in such cases.

A main principle for the UCTE is that the transmission system must be operated in such a way that any single incident, for example, the loss of a line, should not jeopardize the security of the interconnected operation. This is called the *N* – 1 rule. Any deviation from *N* – 1 security must be counteracted immediately. In fact, these events also came to jeopardize stability in the entire UCTE network.

3. Threats

Many kinds of collective and individual violent threats exist, i.e., intentional actions aimed to attack society and its citizens. Some examples are:

- Terrorism:
  - Bombing
  - Armed attack

- Organized crime:
  - Armed attack
  - Bombing
  - Arson
- Individual crime and crime of opportunity.

"Ordinary" criminals, whose motives are usually economical, tend to put some limit on their actions in order not to antagonize society and its citizens too much, and especially not the international society, since this could be detrimental to their goal to earn (a lot) of money! Hence, the really serious threats come from terrorists who seldom show such inhibitions! al-Qa'ida and related terrorist groups have shown low or no tendency to forewarn victims, as was the common practice of, for instance, IRA bombers.

One special type of threat from both "ordinary" crime and terrorism is the "insider," who often by good knowledge of the target, applicable routines and points of vulnerability can add much to the chance of achieving a successful deed (Frost and Ånäs, 1999).

Also, attacks over the Internet can cause severe effects, and in general, society is always second to the criminals when it comes to developing new ways of attacking.

3.1. TERRORISM—PURPOSE AND CHOICE OF TARGETS

The purpose of terrorism is often to achieve political change, for instance, by making society and its functions collapse. The preferred method will then be to disrupt, intimidate, and scare the citizens by killing as many as possible or committing other atrocities. There seems to be less interest for publicity from the "new" terrorists than earlier.

Selected important targets are preferred, e.g., large events with many people present; important symbols, such as the N.Y. World Trade Center; objects with great economic impact on society, such as finance, tourism; and objects causing dangerous collateral effects, such as chemical factories, transports containing hazardous materials. Some structures threatened by terrorism may be:

- Embassies
- Governmental buildings and facilities
- Nuclear power plants

- Sports arenas
- Airports
- Train stations
- Harbours
- Head offices of large corporations
- Hotels and
- Large residential buildings.

However, it was found in evaluating the large-scale bombings against German cities during World War II that indeed smaller attacks that caused electricity, water supply, or other infrastructural systems to break down for shorter or longer periods had a more demoralizing effect on the population than massive attacks with many casualties, which achieved a counter-effect and spurred an increased will of resistance by creating massive hate and anger among the inhabitants.

3.2. TERRORISM—WHERE, HOW, AND AGAINST WHAT?

Terrorist groups of many kinds, many driven by fanatic Islamistic zeal, exist virtually all over the globe (CIA, 2004). Fortunately, there are few world-encompassing networks, the most notorious one being the al-Qa'ida. This is no more a network in the common sense, if it ever was. The international contacts that may have existed previously have been broken up. In many nations, one or more independent national cells may operate on their own accord, having only the religious and moral background and fanaticism in common. Additionally, there may be some loose personal contacts, and general messages communicated and other acts committed may give inspiration and guidance to the local groups.

Core members of such groups seem often to be well educated persons, outwardly appearing as citizens well adapted to society. Graduate or student engineers seem to be a common kind of member, lately, there is also the example from Britain where several medical doctors were found to be members of a terrorist cell. Terrorist operators are usually young, except leaders.

3.3. TERRORISM STATISTICS

The following statistics are based on the time period January 2000–May 2007. All terrorism data are from MIPT (MIPT/TKB), except Figure 1 which comes from the CIA (2004).

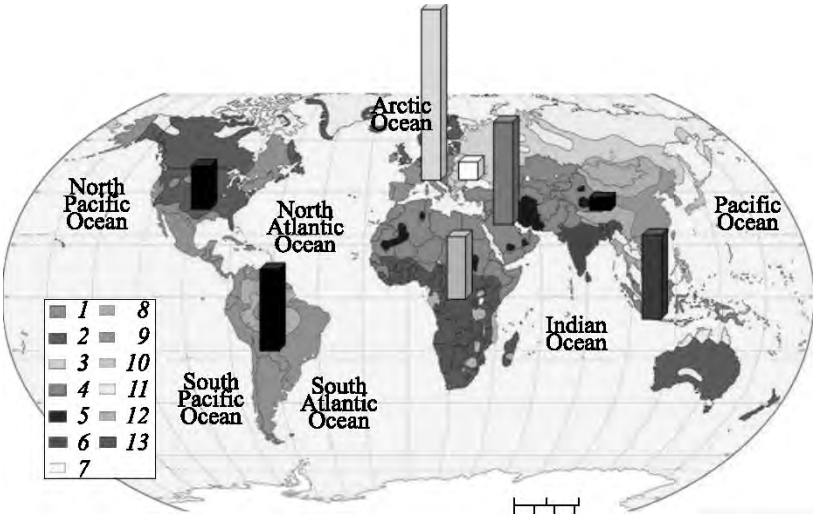

Figure 1. Number of terrorist groups per region. Western Europe = 239.

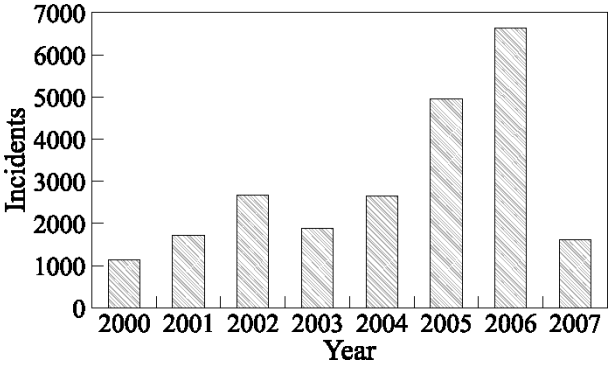

Figure 2. Terrorism, world, incidents per year (-May 2007).

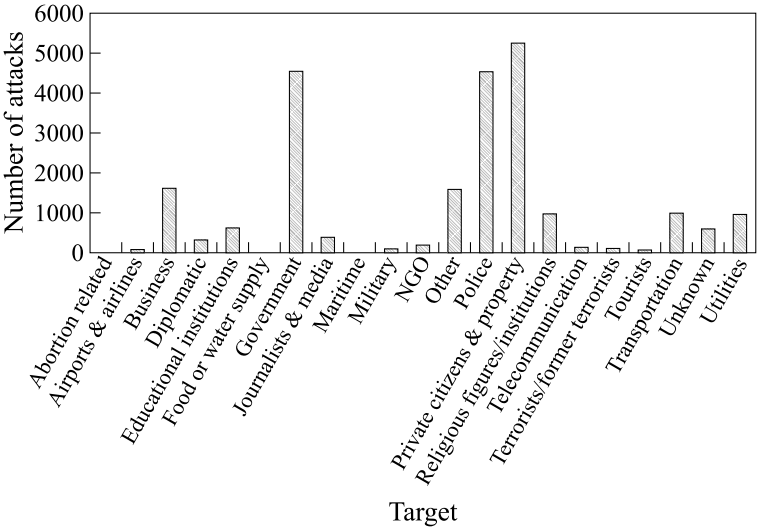

Figure 3. Terrorism, world, incidents 2000–May 2007, by targets.

The general trend of terrorist deeds is increasing worldwide, with many of these committed in Iraq and the Middle East (Figure 2)!

It appears from Figure 3 that the mainly affected targets are private citizens and property, government facilities and personnel, police, and business, with all other targets forming relatively minor parts.

When it comes to the casualties from terrorist acts of different kinds (Figure 4), bombings are the dominating cause, with armed attack in second place and all other means being minor.

In Europe, the number of incidents is going down, much depending on effective counteraction, above all by collecting and exchanging intelligence information between nations (Figure 5 and Figure 6).

It appears very clearly from Figure 7 that the primary sufferers from terrorism in Russia are private citizens, with educational institutions coming second (however, considering that one very large event seriously affected the statistics). These institutions, of course, also contain private citizens, especially, and sadly enough, children.

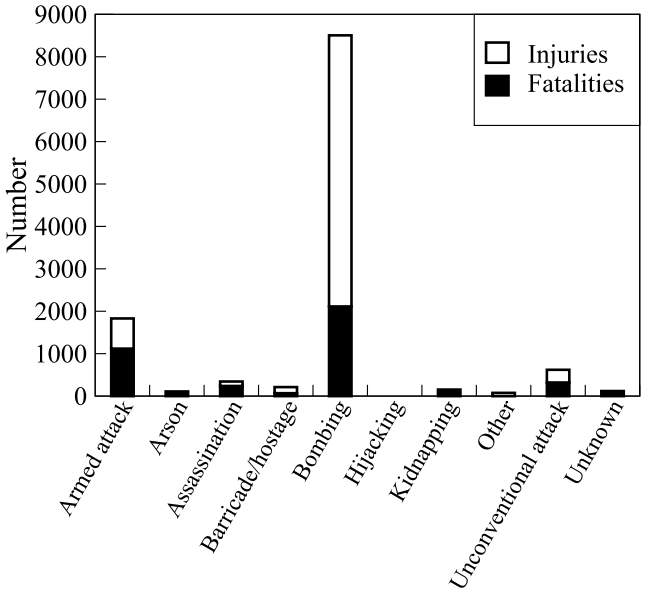

Figure 4. Terrorism, World, casualties 2000–May 2007, by means/methods.

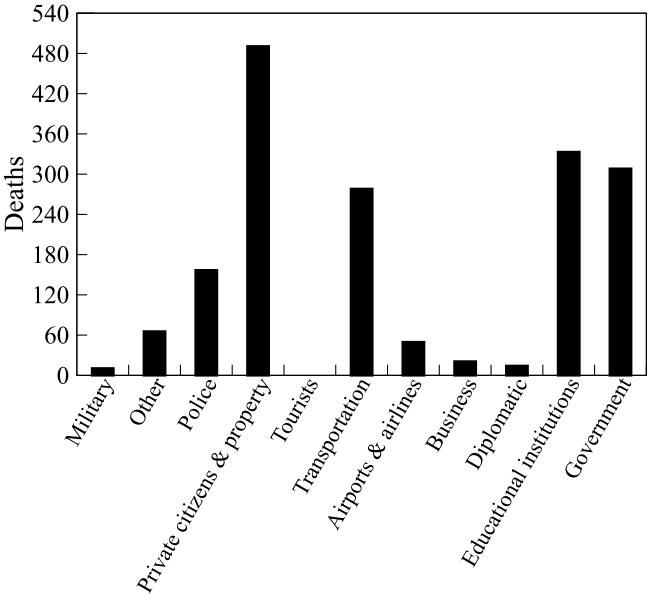

Figure 5. Terrorism, Europe, fatalities 2000–May 2007, by target.

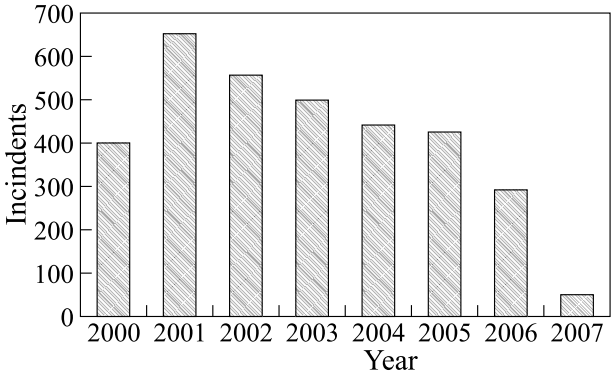

Figure 6. Terrorism, Europe, incidents per year (-May 2007).

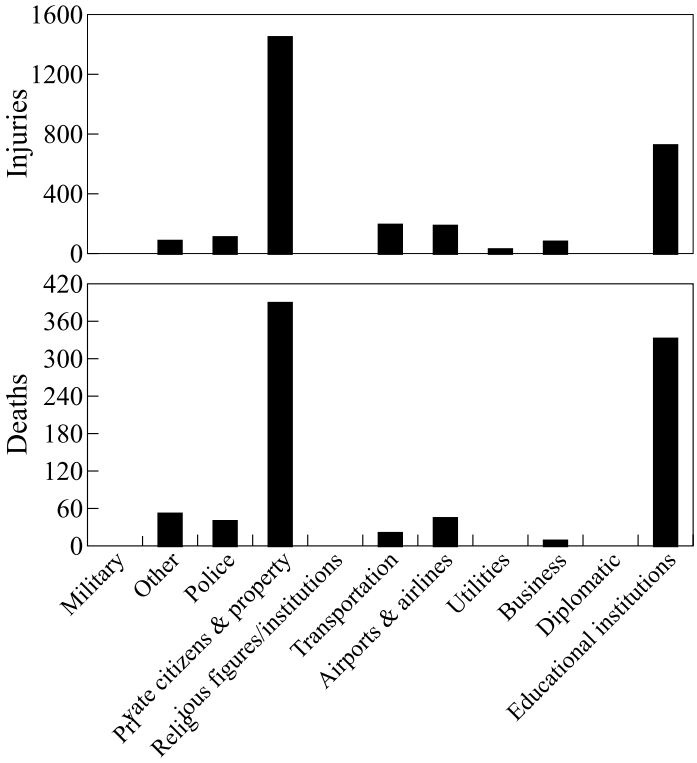

Figure 7. Terrorism, Russia, injuries and fatalities 2000–June 2007, by target.

4. Risks

The number of disasters in society is increasing, both for natural events and man-made (technological) catastrophes (OECD, 2003) (Figure 8 and Figure 9). One categorization can be seen in Table 1.

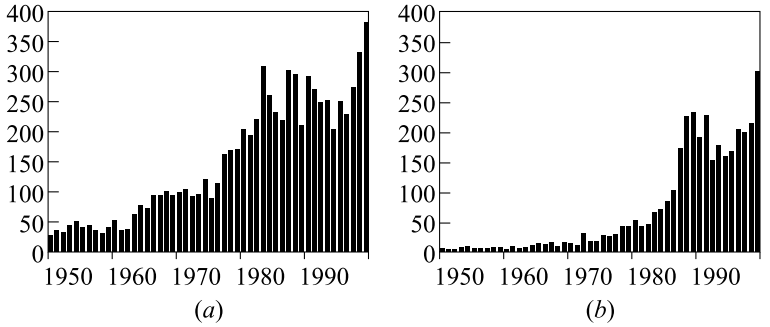

Figure 8. Disasters, events per annum: (*a*) natural disasters, (*b*) technological disasters.

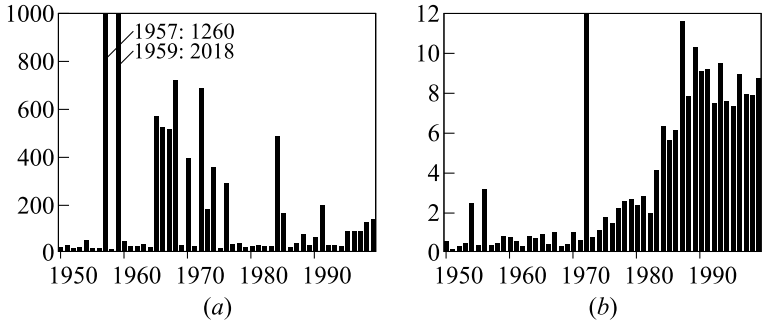

Figure 9. Disasters, fatalities per annum, thousands: (*a*) natural disasters, (*b*) technological disasters (note different scales).

The increasing number of technological/man-made disasters is easy to explain by the urbanization process that has been very forceful in many parts of the world, causing high population densities, and by the international society's large-scale industrialization and increasing complexity. It is more difficult to see a reason for the increase in natural disasters, but it can also be sought in the same development as described, resulting in large masses of people settling at locations which may be less suitable for the purpose, and which may be vulnerable to flooding, earthquakes, and landslides. Consequently, most of these natural disasters are occurring in the developing world.

TABLE 1. Examples of categories of risks.

Natural risks	Man-made risks
Earthquakes	Fires
Volcanic eruptions	Explosions
Flooding	Energy accidents
Hurricanes, storms, tornadoes	Release of dangerous substances
Forest fires	Airplane, ship, train, underground, and road accidents
Landslides, avalanches	Other industrial hazards
Other accidents	Storage and transport of hazardous materials

5. Threats, Means

5.1. CONVENTIONAL WEAPONS

Some examples of conventional weapons which may be used for attacks by criminals and terrorists are:

- Small calibre arms
- Shaped (Hollow) charges, for deep penetration or cutting of hard materials, for instance, in anti-tank weapons such as RPG-7
- GP bombs, shell, mortar rounds, grenades, hand grenades, mines.

Small calibre munitions have undergone remarkable development in the last decades. The advent of armour-piercing projectiles for common assault rifles of 7.62- (Figure 10) or 5.56-mm calibre has meant a great increase in threat level against bullet protected structures. A modern tungsten carbide hard-core, subcalibre projectile may give more than four times the armour penetration of a standard ball round of the same calibre. There are strong strives to control access to such munitions, especially, in the U.S. and Europe. Nevertheless, they now form part of the threat.

Another development which adds to the threat of small calibre weapons is the marketing of calibre .50 (12.7 mm) and 14.5 mm automatic weapons that are relatively light (about 10 kg) and can be carried. Such a weapon gives a muzzle energy of about 20,000 J, compared to

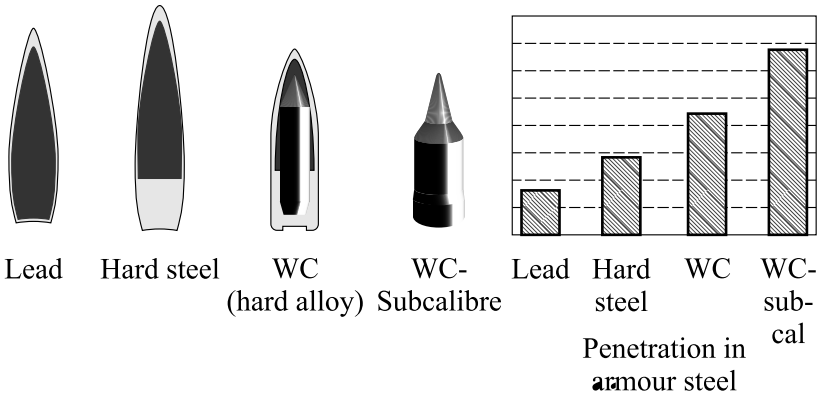

Figure 10. Different kinds of 7.62-mm projectiles and their performance.

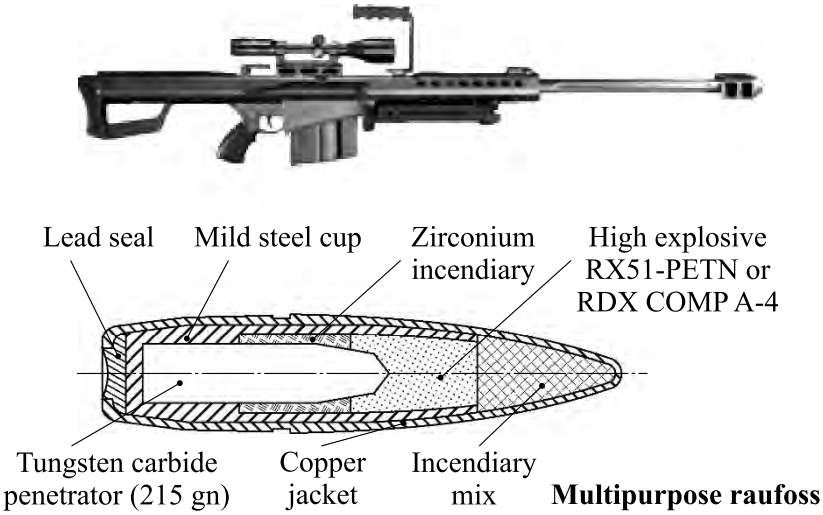

Figure 11. The 12.7-mm calibre automatic rifle, Raufoss "Multipurpose" projectile.

7.62 mm—about 3,000 J, and 5.56 mm—about 2,000 J. The 12.7-mm weapons can supply well aimed fire at 1,000-m range and more. Armour penetrating, incendiary, and explosive munitions also exist for these weapons. To protect against a 12.7-mm bullet (Figure 11) you may need a higher protecttive level than that of a military Armoured Personnel Carrier (APC).

Furthermore, man-portable light anti-tank weapons pack a powerful shaped charge warhead, which can penetrate from 500 up to 1,000 mm of solid steel armour at ranges from 20–30 m up to 400 m or more. There are also relatively light anti-tank and anti-aircraft missiles that can achieve effects out to much greater ranges with great precision. It goes without saying that it will be very difficult to protect a civilian object against threats such as these!

5.2. EXPLOSIVES

Some explosive types, devices, and trends of interest are:

- Future explosives may be 10–20 times more energetic than present ones (Wallin *et al.*, 2004)
- Explosive cutting charges and frames, can also be improvised
- Commercial explosives, packed in letters, CDs, bags, cars, trucks, etc.
- Home-made explosives, such as triacetone triperoxide (TATP), hexamethylene triperoxide diamine (HMTD)
- A common name for bombs and other devices used are Improvised Explosive Devices (IEDs). The IEDs can be made with or without fragments or shrapnel! They can contain many different explosive materials, such as:
  - Commercial: dynamite, etc., Ammonium nitrate and diesel fuel (ANFO)
  - Military: plastic explosive (i.e., RDX or PETN powder and oil), TNT, or Comp B from standard munitions or demolition charges;
  - Homemade: TATP, HMTD, fuel–air mixtures (LPG, LNG), thermobaric charges.

An IED can be of size from some grams in a letter bomb, via a suicide bomber's body load of up to 10 kg, a car bomb typically containing 100–600 kg, up to many tons loaded on a truck, or even thousands of tons on a ship!

A typical car bomb of 600 kg ANFO will create considerable fragmentation effect. Fragments and larger parts will be projected at high speed and may reach a distance of up to 500 m. It will also cause a powerful blast, capable of crushing windows at a radius of hundreds

of meters. It will disintegrate the car almost completely, and few parts may be retrieved afterwards. The detonation will typically create a crater in the ground of about 1½-m depth and 3 or more meters of diameter.

Improvised explosive devices are commonly initiated by commercial or home-made detonators, which may be actuated by different means: direct electric (cable) signal, mobile phone, two-way communication radios, tripwires, infrared motion detectors, commercial remote control devices. Some terrorists have shown high ability to adapt their means of triggering IEDs to counteraction.

A detonation of an explosive also has considerable incendiary effect. Since normally the detonation will break up and fragment nearby items, a fire arising may find plenty of readily combustible fuel in the debris created.

5.3. INCENDIARIES

Incendiary weapons can be made for military purposes or easily be home-made. They can be designed with:

- Home-made incendiary bombs/grenades filled with petrol or other highly inflammable substances, such as “Molotov cocktails”
- Arson with combustible substances and triggers from a simple candle to more sophisticated electric and electronic devices
- Metallo-organic substances, some of which are pyrophoric
- Pyrophoric metals, like zirconium, or white phosphorus.

5.4. FUEL–AIR MIXTURES

- High-pressure charges (thermobaric charges) consist of a metal powder and a volatile liquid dispersed in the air, and then initiated.
- Acetylene, methane (LNG), propane and/or butane (LPG), fuel–air explosives (FAE), spread inside a closed room and then initiated.
- Larger amounts of such substances spread in free air can also become explosive.

A fuel–air mixture may contain 10–20 times more energy per kilogram of fuel than a high explosive. Transports containing highly energetic

volatile fuels, including petrol and fuel oils, must be considered when making risk assessments, and will also constitute a potential source of terrorist threat! One tank truck with trailer loaded with 50 t of fuel can contain as much energy as 1 kt of high explosive! One LNG or LPG transport ship carrying 100,000 t of gas contains the same energy as a 2-Mt nuclear warhead!

It should be pointed out that fuel–air mixtures, and especially, thermo-baric charges, also have a high incendiary effect, and may even ignite objects at distance by thermal radiation.

5.5. CHEMICALS (C)

Examples are:

- Chemical warfare agents and other noxious chemicals. Examples are nerve gases, mustard gas, chlorine, hydrogen chloride or sulfide.
- Hardening substances, such as rapidly curing construction foams creating hard or tough surfaces. They can be used to obstruct motion, silence alarms, etc.
- Etching and corrosive agents can affect optical equipment, such as hydrofluoric acid which etches glass, and different solvents which will have a similar effect on plastic lenses.
- Soft, water-containing foams can attenuate sound and reduce blast pressures from a detonation.
- Fuel destruction chemicals, can destroy fuels for cars, trucks or aircraft.
- One of the main problems with C agents is to spread them. This makes it attractive to use an existing way or system to do this, such as ventilation.

5.6. ELECTROMAGNETIC (EM) WEAPONS

There are two main types of microwave/millimetre wave weapons:

- Non-Nuclear EM Pulse (NNEMP), wide-band, usually explosively driven, compact weapon, creating an ultra-short, wide-band pulse of radiation.

- High-Power Microwave (HPM) devices, large or relatively small, driven by a power source or an explosive generator, creating one or several short bursts of narrow-band radiation.

The NNEMP and HPM devices can be powered by conventional power sources and made small enough to be built into an ordinary attaché brief-case. They can also be driven by an explosive pulse generator. Some such devices can be made of the size of a coffee cup. They may not cause much noise; indeed, less than an exhaust explosion from a car.

Both kinds can have adverse effects on and even destroy sensitive electronic circuits, such as computers, mobile phones, other telecommunication equipment and car engine control chips. Whereas military targets, such as combat aircraft, can be hardened, most civilian electronics are very vulnerable and cannot easily be protected for cost reasons! The miniaturization which continues usually adds to sensitivity. In addition, it may be difficult to prove that an attack has occurred and that failures in an IT system have not been caused by a lightning strike or "glitches" in the ordinary electricity supply! Electromagnetic weapons might kill an industry or sensitive infrastructural communications and computers!

Also, lasers with different effects, such as cutting material, even highly resistant metals, or disturbing or destroying optical sensors and human eye-sight, can be made to constitute serious threats.

A standard commercial infrared laser affecting the eyes of a person may not be perceived by the victim until it is too late and serious damage, dazzling or temporary or permanent blindness has been caused. The effect will be enhanced if the target uses an optical instrument, such as binoculars. Filters or goggles which preserve some degree of vision through them are generally not very effective since they will only protect against one or a range of wavelengths.

5.7. NUCLEAR (N) AND RADIOLOGICAL (R) WEAPONS

Some potential terrorist threats may be:

- Midget and "primitive" nuclear warheads made by terrorist organizations, possibly rogue state supported.
- Radioactive materials ("dirty bombs") for spreading against persons, electronics, facilities, drinking water sources, etc. will cause

damage and require decontamination. Candidate materials, such as CO_{60}, can be found in considerable industrial or medical applications.

5.8. BIOLOGICAL (B) WEAPONS

Rapid bio- and geno-technological development may enable design of effective B agents, also for terrorist organizations with limited resources. Effects, against humans and domestic animals, may include:

- Poisoning, such as spreading bacteria to drinking water
- Performance reducing agents and
- Contagious diseases, such as anthrax, smallpox, genetically modified influenza.

Some B agents, such as anthrax or foot-and-mouth disease, could put entire populations of domestic animals in jeopardy. This latter type of attack may be a more probable one than an attack on humans, and might cause serious economic and logistic problems for society.

5.9. BOMB THREAT VEHICLES

An IED can be carried on a person, such as a suicide bomber, or on vehicles or vessels of widely varying kinds, such as cars, vans, trucks, small boats, merchant ships, airliners. The ordinary appearance of the delivery vehicle will be an important prerequisite to the terrorist.

5.10. TERRORISTS' CHOICE OF MEANS

Although few "unconventional" attacks have occurred, they pose quite a serious threat, among other because

- al-Qa'ida's strong interest in CBRN agents persists, finally aiming at nuclear arms!
- There may be considerable risk for unsophisticated C attacks.
- Comprehensive instructions to manufacture improvised chemical weapons exist.
- Anthrax is judged to be the most probable B agent.

- There are also detailed instructions available for constructing "dirty bombs" (R weapons).

A dirty bomb exploding in, for instance, a major harbour, will be likely to close that facility down for months on end. It may also cause other harbours to be closed to avoid being subjected to similar attacks, with ensuing severe consequences for society and its citizens.

6. Urban Vulnerability

The situation for societal infrastructure is changing rapidly, among others (Fischer, 2003):

- Society is becoming increasingly dependent on technological infrastructure.
- Technology development, especially in the IT-sphere, continues to be extremely strong.
- Technical standardization is done in an international environment, often based on a *de facto* situation, and controlled by large industries rather than governments. The international standards for mobile telephony provide valid examples.
- Changed patterns of activity are propagating, caused by privatization, outsourcing, globalization, relocalization.
- International dependencies are becoming much stronger. Most nations are increasingly dependent on food supply and other support from others.
- The "just-in-time" concept means that there are no more large storages available. For instance, food supply present in a city like Stockholm will last only a few days if transports are totally interrupted—the great bulk of supplies will be present on road, maritime, and air transports at any time!
- There is and will continue to be reduced Government control and more of market influence. Private enterprise takes over more control of important infrastructures, such as water supply, telecommunications, electricity, and other energy supply.
- Liberalization and internationalization of markets. Large, multinational corporations may get much more influence than a state on issues important to public safety and security.

- There are rapidly changing threats (such as asymmetric conflicts, crime, terrorism). These threats are also spread very rapidly between nations.

Consequences of disturbances of critical infrastructure may be difficult to identify. Direct effects are usually easy to identify (Wallin *et al.*, 2004), but indirect effects can be much more difficult to trace, due to

- Complex dependencies
- Chain effects (higher order effects)
- Threshold effects
- "The last straw that broke the camel's back" and
- IT-related attacks on infrastructure have occurred, for instance, against the Internet and telecommunication systems.

Urban areas are characterized by high densities of buildings and infrastructure, as well as of population. Targets especially vulnerable to terrorism may be those where there are great masses of people assembled, such as airports, stations, public transport, large sports, or cultural events.

6.1. POWER SUPPLY

A general trend seems to be that society is becoming more dependent and less resistant to power disturbances. For instance, financial transactions have back-ups that permit restoration of all occurring before the disturbance. But in case of a longer power outage, it will not be possible to return to a manual process, and the system will cease to operate. The situation is similar for milk farming which is now so dependent on machines and automatic equipment that it will not be feasible to go back to manual milking or providing forage for the cows.

6.2. WINDOW CRUSHING (FORSÉN AND SELIN, 1991)

A scenario example can be described, applied to an urban area with a population density of 650 persons per hectare, and with window panes in the area made of normal machine glass, size 1.25×1.55 m $\times$ 6 mm. A 2-t high explosive charge is detonated on the ground.

This will be likely to result in the following damage:

- Nearby buildings may be seriously damaged
- Persons close by may get seriously injured by blast and fragments
- Persons further away may also be injured by fragments, by debris thrown, or be thrown themselves by the force of the blast and
- Persons even further away may get hearing damage.

At a radius of 300 m, all windows will be crushed, but at radius 600 m, in principle, you will be safe. If all the windows within 300 m are crushed the outcome will be that about (Kummer, 2004)

- 1% of persons exposed will be killed
- 10% be seriously injured and
- 100% be subject to light injury.

This means that

- 180 persons will be killed
- 1,800 will be seriously injured and
- 18,000 will sustain light injury.

These results refer only to the damage caused by the broken windows. If nearby buildings are of a structure that can easily collapse, such as happened in the Oklahoma bombing of 1995, the number of casualties can increase much.

In addition, the geometry of the city layout, the placement of the bomb, and the meteorological conditions, such as temperature inversion, may considerably influence the results. The blast will be "channelled" along the streets leading from the bomb emplacement, such as is shown in Figure 12.

Windows facing the blast are more prone to damage than those receiving a grazing impact, and windows at the back of buildings show much less tendency to break.

Generally, the damage caused by fragmenting windows can occur quite far from the site of the blast, at locations not having any connection with the intended target, and can affect great amounts of people. It is, however, relatively easy and inexpensive to protect persons in a building against this kind of hazard.

Figure 12. Map of "channeling" of blast caused by a bomb consisting of about 50 kg of HE, located at the fourth floor, Stockholm, 1982.

6.3. STRUCTURAL DAMAGE

At the bombing of the Alfred P. Murrah Federal Building at Oklahoma City, 1995, the threat was similar as for the example just described, i.e., a 2,200-kg truck bomb at ground level outside the building. The explosive used was ANFO. Building collapse occurred at a radius of 30 m.

The result was that 1/3 of persons in area were killed. However, as many people in this bombing were killed or injured by broken window fragments as by the collapse of the part of the building. It has been questioned (Partin, 1995) whether the truck bomb only could cause the collapse, and whether there were not also demolition charges emplaced at some of the supporting pillars.

Be that as it may, this example and the 9/11 WTC catastrophic deeds in 2001 show that buildings that collapse will cause excessive loss of life, unless full evacuation can occur before the bomb is detonated!

A building attacked by an external bomb of considerable size will get excess loadings over a large part of the building structure. However, an internal loading of much smaller size will mean more concentrated

overloads on the structure (Forsén, 1987). The structure and walls of the building will contribute to confine the blast and ensure good coupling to the structure. Gas explosions inside a building may also, due to the confinement, cause great damage inside a building. Especially in buildings of precast elements, an explosion in a room may cause local damage that may trigger a collapse. Also "domino" effects can arise, i.e., that one inside wall will collapse, enabling the explosion to hit the next wall at full power, etc., etc. This type of event may cause damage at long distance from the site of the explosion. The blast waves can also propagate long distances along corridors, lift shafts. stairwells, etc. with low attenuation.

7. Protection and Mitigation

7.1. POWER SUPPLY

Four main strategies were proposed by FOI to reduce the dependence of the Swedish society's essential functions on continuous power supply (Frost *et al*., 2004):

- Reserve power. Some recent violent storms in Sweden have, especially, made many agricultural units invest in reserve power supply. This could be done for all important functions of the Swedish society at a cost below 1 GEUR (2004).
- Increased possibility to prioritize and redistribute power supply. This is also feasible, especially, in simpler alternatives, at costs up to 800 MEUR, but may cost up to 2.1 GEUR for full coverage. (*However, modern technology with remotely controlled meters may enable more advanced options, and can be financed by reduced cost for the reading of meters. Authors' comment.*)
- Increased robustness of the power supply system. This will be expensive, or up to 5 GEUR, but limited measures for protecting stations, central control offices, and communications can be achieved at around 300 MEUR.
- More rapid repairs of the Power System. This can be achieved at investment levels below 1.3 MEUR, and includes increased repair capacity and coordination, better communications and reserve power for the most time critical activities.

7.2. WINDOWS

Measures to be implemented in a protected building design include: reduced window area on wall, smaller window panes, increased glass thickness and more resistant glass materials (tempered, laminated) (Figure 13).

A great variety of glass designs for increased blast protection are commercially available, including:

- Multiple layer glasses (alternating glass and plastic sheets).
- A plastic layer on back, i.e., of strong polycarbonate, will stop the window from fragmenting and being thrown in.
- Better fixation in the frame adds much to the resistance of the glass. Suspension of the window pane in elastic joints will serve to reduce tensile stresses.
- Reinforcement of corners. The corners cause high stress concentrations, which can be relieved if they are more solidly suspended than the rest of the pane. Elastic joints are important also here.
- Fragment collecting curtains. Simple nylon tulle curtains, considerably longer than the height of the window, have long been used to protect personnel in government buildings in the U.K. If the window is fractured by blast, the curtain will form a bag net and collect the debris.

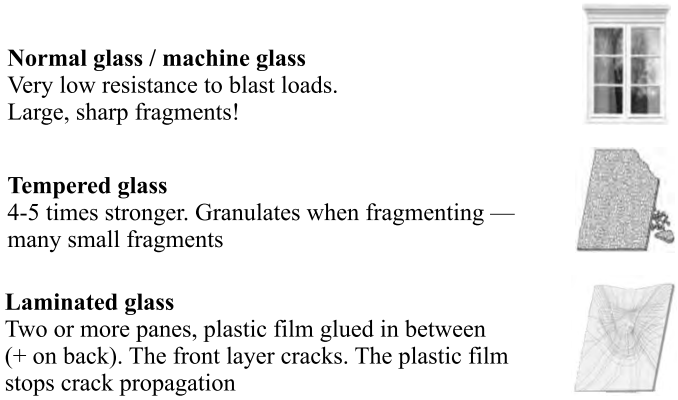
Normal glass / machine glass
Very low resistance to blast loads.
Large, sharp fragments!
Tempered glass
4-5 times stronger. Granulates when fragmenting — many small fragments
Laminated glass
Two or more panes, plastic film glued in between (+ on back). The front layer cracks. The plastic film stops crack propagation

Figure 13. Properties of different glass designs.

- Collection devices/rod or wire can be added to laminated windows, which, although they may not fragment, may be thrown inwards in their entirety. A solidly fixed wire across the centre of the window will serve to catch it.

The simplest and most economical way to reinforce existing windows may be to apply self-adhesive special plastic foil sheets, which are commercially available, to the inside, or to add an extra layer of polycarbonate, solidly fixed inside the window.

When reinforcing windows, one has to assure that the window frames and their fixation to the building wall will be correspondingly strengthened in order to avoid that the entire window and frame can be thrown into the building and cause extensive damage.

Bullet-proof glass can be added to specially exposed areas, such as bank offices, embassy entrances, or bullet protected cars. They have to be chosen according to the actual threat. As has been shown, there is now a great variety of small calibre munitions with superior penetration ability. To protect against these will require very thick transparent armour, sometimes so thick that visibility through it may be impaired. The heavier threats such as calibre .50 or .60 ammunition are even more difficult to stop, and especially against light anti-tank weapons it is not feasible to use transparent armour designs.

Another important reason to reinforce window-panes of buildings, at least on the lower levels, will be to prevent explosive charges, incendiary bombs or inert projectiles from being thrown in through the windows at situations like riots or similar. Also, terrorists may prefer this way of attacking a vulnerable target.

7.3. STRUCTURAL DESIGN

In Sweden, both residential and industrial buildings were classified (Dellgar *et al*., 1993; Elfving, 1997b), according to their resistance to various types of overloads, such as from blast or impact. The main are described in Table 2.

Within each class, there are numbered subdivisions, describing the internal structure, such as type of joists, the type and weight of external walls, and special characteristics of the building.

TABLE 2. Main classes of type buildings.

Class	Type
B	On-site cast reinforced concrete
M	Brick walls
P	Prefabricated concrete (elements)
S	Steel frame
T	Wooden frame

This leads to about 20 different "type buildings" to approximate most residential and industrial facilities built in Sweden. For each type, a number of typical properties describes the frame structure, subdivisions, rooms, internal walls, etc.

Most of these type buildings give good protection against fragments coming from above, whereas, in general, protection against horizontal fragments and projectiles was poor, and the resistance against contact detonations and shaped charges was very poor (Elfving, 1997b). Resistance against air blast loads was good for buildings having an on-site cast reinforced concrete frame (Elfving, 1997b).

As shown above, collapse of building structures will be likely to cause a high number of casualties and especially a high number of fatalities.

Generally, resistance to blast requires similar properties in buildings as the ability to withstand earthquakes, such as:

- A flexible frame, able to deform and absorb energy without total loss of integral strength.
- Redundancy, i.e., ability to withstand the loss of one or more supporting pillars or beams without building collapse.

Some efforts were also made at FOI to analyze international building structures (Elfving, 1997a). The study encompassed some areas of Eastern Germany, Bosnia-Herzegovina, and some parts of Asia and Africa. The results were not encouraging, and it turned out to be difficult even to obtain detailed information on the design of buildings. For the latter two areas, available information consisted of general descriptions of traditional architecture outside urban areas.

7.4. SOME GENERAL RISK REDUCTION MEASURES

Some ways of reducing the vulnerability of buildings and facilities were described above. Such measures should not be applied alone, but seen as part of a integral solution. Such solutions may include:

- **Access control**, especially, to hinder unauthorised persons, cars, and trucks from approaching the building or facility in question. Access control is best achieved by fences, walls, barriers, and similar, guarded by security personnel.
- There exist many kinds of **sensors** for surveillance and intrusion detection, such as infrared, other optical, microwave-based, or other types. They, for example, video cameras, can be effectively used to support manned surveillance. There are also video-based systems that sense changes in the image and will trigger an alert!
- To increase the closest **distance** at which an explosive event can occur, be it an attack or an accident, is a most efficient measure to reduce its effects.
- **Impact barriers** are used to avoid that a heavy car or truck can drive into the building. Some such devices have the form of a short pillar that can be lowered into the ground in order to permit authorised passage.
- **Walls, slopes, and gradients** can be used to hinder access without obstructing views and appearance too much. They can also be used to protect the facility from being hit by fragments and/or to deflect blast waves that impact them.
- The **ground** around the building should be effectively used to ensure that unauthorised presence can be avoided. A park around a building is one of the best protective means. If need be, this may also enable an easy increase of the security perimeter zone around a threatened object.
- **Vegetation** in the form of larger trees is an effective means of obstructing passage of cars and trucks, while being perceived as a pleasant addition to the urban environment. Such vegetation, made dense enough, can even serve to shield against blast.
- The use of **special windows—**strength, size, glass materials, mountings—has been mentioned earlier, and can save many lives in case of accident or attack at relatively low cost.

- **Facade** materials should fulfil similar requirements as the windows, i.e., to deflect blast waves without breaking, and to stay securely fixed at their original location. In addition, it will be desirable if they can protect from fragments or projectiles that may hit them. High performance reinforced concrete panels are promising for this purpose.
- **Load bearing walls and frame construction** must be designed to be able to resist dynamic loads by being elastic and able to absorb energies from actions that may affect them without disintegrating or being too much weakened, be it from an earthquake or an explosive charge exploding nearby. Especially, it is important to ensure that the building will not collapse.
- In placing of **entrances** and **emergency escape routes,** the need to rapidly evacuate persons from the building should be considered, taking into account that an attack or accident could occur from unexpected or multiple directions, perhaps, blocking important escape routes or rendering them unusable.
- **Shelters** of simpler or more qualified type can be placed close to where people work or reside. It may take too long or be impossible to evacuate or go to a larger shelter in the cellar and then such shelters will offer a possibility of survival, long enough to be rescued. They can be supplemented with air-breathing equipment, etc. This type of shelter is becoming frequently built in tunnels. For seriously threatened facilities, there should be at least one such shelter located at each floor.
- Placing of **air inlets**, central shutting-off of **ventilation,** etc. are important measures to ensure that noxious or inflammable gases and fluids cannot be spread into the building. Air inlets should be placed not to be readily accessible from the street level outside the building but higher, at least 4–5 m above. Also, roofs may be vulnerable to attack from the air, or from terrorists who clandestinely make it up there in order to spread some B or C agent into the ventilation intake. To be effective and respond rapidly enough, a central shut-off system should be complemented by sensors for feasible threat substances.

- Also **control of fire doors and ventilation system in case of fire** must be considered. Generally, it is the smoke that causes excessive casualties and fatalities, not the fire *per se*!

8. Research and Technology Resources and Facilities

8.1. FOI RESOURCES AND ACTIVITIES

FOI (www.foi.se) has excellent theoretical and empirical knowledge, numerical models and ample experimental facilities to study most subjects connected with urban threats, risk, vulnerability, and protective means. They include:

- Small-scale experiments and simulations, e.g., on protective abilities of building structures and elements to blast, fragment, and projectile loads
- Large-scale experiments. At the Älvdalen firing range, FOI can perform experiments on and below ground with hundreds of tons of ammunition or large explosive charges
- Projectile penetration. FOI has firing ranges from small calibre up to 105 mm
- Blast loading. Facilities are blast tunnels and open-air blast loading facilities, including combined fragment and blast loads
- Fire and smoke. Miniature and up to full-scale studies of fire and smoke spread. A unique method to study the spread of hot simulated smoke in new buildings and facilities enables integral full-scale study of the function of the safety systems installed! At most such tests, serious deficiencies are detected and can easily be rectified before anybody runs the risk of getting hurt and
- Studies and forensic work on live bombings and explosion accidents. FOI has an ample database of accidents and sabotage actions

8.1.1. *Evaluation Models*

VEBE (Holm *et al.*, 1995) is a computer model for simulation of attacks and disasters in urban areas. Figure 14 shows an example of the outcome of an attack, in this case involving 42 GP bombs of 500 kg each dropped over a city.

The area map (Figure 14) shows (regrettably, without colour):

- The bomb pattern and location of individual hits
- Craters arising
- Buildings hit
- Buildings collapsed
- Debris filled zones and
- Burning buildings.

The smaller windows describe the situation in a selected building and will show damage zones and fire and smoke filled parts.

The VEBE code can be run both in Monte-Carlo and deterministic modes. Application areas include damage prevention, rescue activities, training of rescue personnel and central and local emergency planning.

Input to the code consists of location, geometry and type of building, weapon or charge characteristics, and location of people.

Calculation modules include penetration; blast characteristics, damage from blast, fragments, building collapse, fire initiation and damage (the fire and smoke module is time-dependent, showing development and spread of the fire).

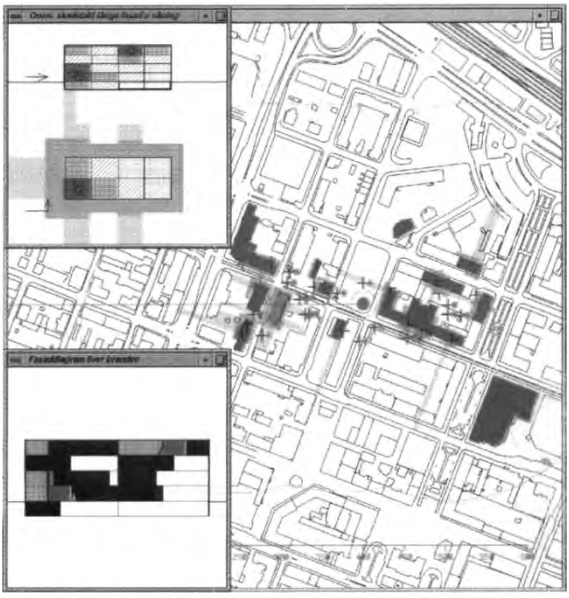

Figure 14. Output chart from VEBE code.

Output is presented as:

- Injuries and fatalities
- Damaged buildings (zones)
- Ground (cratering and damage to pipes, cables, etc.)
- Debris zones and
- Graphic output (see above).

The VEBE code is well established and verified with experiments, and will execute on a PC. Many computations can be done in a short time in order to study, for example, the effect of various protective measures contemplated, or the rescue resources needed to successfully cope with specified disaster scenarios.

Another special model for evaluating levels of protection against sabotage and terrorist deeds was also developed at FOI (Lindqvist *et al*., 1999). It was tested on various facilities within the county of Stockholm and found to work well.

A large gaming exercise to study dependencies between different parts of society was also performed in 1991–1993, the so-called "Stockholm Study" (Lindqvist *et al*., 1993), in which the city was subjected to a medium-scale military attack ("strategic assault"). At the initial stages, extensive sabotage was performed against various targets. Such gaming studies can also suitably be performed in connection with exercises. One problem arising was to be able to accommodate, handle, and systematize the very large amount of data generated! There are now models and databases available to cope with this problem.

8.2. SECRAB RESOURCES

SECRAB Security Research (www.secrab.eu) is a young company dedicated to Security, Safety and Defence Research and Technology, but with wide and extensive experience within the area. SECRAB assists Customers to find problem solutions by giving access to the best competences available in Europe as brokers for Security, Safety and Defence Research and Technology, assists customers to organize, manage and execute research and technology programmes, projects or courses, and to set up or participate in Research and Technology Project applications for the European Union, including FP7, the U.S. Department of Homeland Security/HSARPA and DoD/DARPA.

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RISK EVALUATION OF TERRORIST ATTACKS AGAINST CHEMICAL FACILITIES AND TRANSPORT SYSTEMS IN URBAN AREAS

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Abstract: Terrorist actions have increased in recent years. In the past, terrorist attacks or sabotage have been considered as a security problem but their frequency means they must also be considered from the safety point of view. A complete risk analysis must include scenarios caused by terrorist attack or sabotage. As well as chemical plants and storage facilities, characterized by the presence of large quantities of dangerous substances, also road/rail tankers used for their transport constitute potential targets. The hazard associated with transportation depends on the vulnerability of the territory. This paper focuses attention on the description of a methodology for the analysis of incidental scenarios caused by terrorist attacks in urban areas and the identification of some aspects where improvements can be made. Finally, an application of this method is illustrated. Furthermore, in order to obtain a complete risk analysis, it is necessary to take into account that, beyond substances transported, the consequences depend on the mode of attack and the characteristics of the infrastructure and territory.

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1. Introduction

Terrorist attacks have increased in recent years. As result of 09/11/2001, the attack to the Twin-Towers and the Pentagon, it has been considered necessary to develop and implement counter terrorist measures for all activities involving the handling and transport of dangerous substances. Particular attention must be paid to the transport of dangerous substances as the hazard may be greater than that for chemical plants because of territorial vulnerability.

There are also other meaningful events that have taken place in transport systems, in particular, the incident of the 03/11/2004 in the suburban rail system of Madrid. There were a series of explosions aboard trains and in some railway stations, with a total of 198 dead and 1,274 injured.

On the 07/07/2005, the first day of the 31st G8 Conference, three bomb explosions occurred on London Underground trains, and another bomb destroyed a bus in the city center, 56 people were killed and 700 injured in the four explosions. The attacks are the first suicide attacks in Western Europe. Some days later, on 07/21/2007, there were three small explosions on the London Underground system and on a double-decker bus. This was called as a “major incident” rather than an attack, and only minor injuries were reported. These bombs were intended to cause as much damage as the 07/07/2005 London bombs, but the explosives had deteriorated and failed to detonate. It is necessary to mention the incidental scenarios caused by terrorist attacks or sabotage during the transportation of dangerous substances. On the 07/22/2005, in Iraq, there was a very serious terrorist action, an attack caused the explosion of a road-tanker transporting gasoline, while it was parked near the Shiite Mosque of Musayyib, south of Baghdad. At least, 60 dead and 82 injured were reported. More recently, on 03/27/2007 in Tal Afar, Iraq, the explosion of two road-tankers transporting a toxic product, probably chlorine, killed 152 people and injured 347. Chlorine has been used in suicide attacks in Iraq five times. In May, a suicide truck bomb killed 50 people and injured 115 in Makhmur; in June, a

truck bomb blast on a square near to a mosque in Baghdad killed 75 people and wounded 204.

In June 2007, police found two car bombs in central London and was able to prevent their explosion. Less than 38 hours later, two men rammed a jeep into the terminal building of Glasgow airport. The three car bombs contained large amounts of propane and gasoline. The bombs were possibly meant to be an explosively-actuated incendiary devices. Such devices, more commonly called firebombs, work by using a relatively small low-intensity explosive charge to ignite a more volatile flammable material. This results in an intense, rapidly spreading fire that can quickly engulf a confined space such as a building, or a semiconfined space such as an urban area. Powerful explosively-actuated incendiary devices are extremely difficult to make, the main problem is getting the explosive charge to ignite the flammable material. In many cases, the initial explosion merely hurls the tanks or otherwise fails to puncture them or ignite the gas or it damages them to the point that the gas leaks out harmlessly. The amount of flammable gas apparently recovered in these incidents would have been sufficient to create massive fireballs, though in order for the device to reach its full explosive potential, it would have to be carefully designed with a precise mixture of fuel and air.

2. Aims

The main aim of this paper is to combine security and safety in order to study events which concern both. The topic of security is to prevent actions such as thefts, sabotage, intrusion, etc. and generally security is managed with intelligence measures, physical measures, and procedures to defend the patrimony. Safety mainly regards the risks associated with human activities (production, handling, storage, and transport of dangerous substances) and natural phenomena (earthquakes, hurricanes, etc.). In context of industrial risks, safety aims to identify and prevent all the potential undesired events due to errors or unexpected failures, causing process deviations. Thus, safety is managed with preventive and protective measures.

This work tries to determine an effective approach that allows the measurement of the possible damage due to a terrorist action during the transport of dangerous materials (safety) and give some fundamental

elements for more effective actions of prevention and protection (security) for people who have to manage such incidents. As well as chemical plants and storage facilities, characterized by the presence of large quantities of dangerous substances, also road/rail tankers used for the transport of such goods constitute a potential target; moreover, the hazard associated with transportation depends on the vulnerability of the territory. This paper focuses attention on the description of a methodology for the analysis of incidental scenarios caused by terrorist attacks and the identification of some aspects to improve. Finally, an application of this method has been shown. In order to obtain a complete risk analysis, it is necessary to take into account that, beyond substances transported, the consequences depend on the modality of the attack, the characteristic of infrastructure, and territory.

3. Risk Assessment of a Terrorist Attack

The management of the terrorism risk is very complex, it requires a systematic and structured methodology that permits an exhaustive analysis of the possible modes of attack and the definition of the vulnerability for the system concerned. The main object of this paper is to outline an approach for the analysis of incident scenarios generated from terrorist attacks in the transport of dangerous substances (Lisi *et al*., 2007), this method will be a useful support in order to define the best actions for their prevention and mitigation.

The approach used in this paper can be summarized in the following scheme:

- Characterization of the areas considered potential targets for terrorist actions
- Definition of the characteristics of the area (manufacturing site and/or characterized by transport of dangerous substances)
- Qualitative study (identification of incidental scenarios) and
- Quantitative study of the incidental scenarios.

The first and the second phase of the method regard the census of all the information characterizing the area in which there is the potential terrorist target, such as a manufacturing site which can also be characterized by the transport of dangerous substances. These steps therefore

comprise the collection of information regarding chemical plants and the associated transport.

3.1. IDENTIFICATION OF POTENTIAL TERRORIST TARGETS

The aim of sabotage or terrorist attack is not only to create the greatest possible damage, but also to destabilize normal life. As a consequence, urban areas and critical infrastructures should be protected against terrorist actions. Generally, the sites, considered potential targets, are characterized by some strategic elements. This list shows a sufficient number of elements but it is not exhaustive:

- Public buildings
- Areas with a great presence of people for particular events
- Public transport systems
- Telecommunication systems
- Public utilities, gas, water, electricity
- Areas of great commercial importance
- Areas of historical importance
- Handling and transporting activities of dangerous substances
- Chemical activities classified as major hazards.

In order to identify potential terrorist target, it is necessary to develop a methodology based on an index method. In 2003, the American Petroleum Institute and National Petrochemical & Refiners Association (API-NPRA) have developed a methodology to provide assistance by facilitating the development of sector-specific guidance on vulnerability analysis and management for critical asset protection for the chemical manufacturing, petroleum refining, and liquefied natural gas (LNG) sectors. This activity involves two key tasks for these three sectors:

1. Development of a screening to supplement the Department of Homeland Security (DHS) understanding of the assets that are important to protect against terrorist attack and to prioritize the activities.

2. Development of a standard security vulnerability analysis (SVA) framework for the analysis of consequences, vulnerabilities, and threats.

3. A second approach to the problem of the vulnerability of chemical plant to terrorist attack is described in a report by the Stör-Fall Kommission (SFK), German Hazardous Incident Commission. In view of 9/11/2001, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) requested the Hazardous Incidents Commission (SFK) to investigate the conesquences arising from the new threat situation in the field of installation safety. The results of its deliberations are set out in a Guideline.

   This Guideline describes the following issues:

   - Proposals regarding the extent to which the safety report and the emergency plans should cater for preventing attacks and minimizing the consequences of attacks.

   - Proposals on the extent to which the General Administrative Provision on the Major Accidents Ordinance, prepared by the Ministry, should take account of interference by unauthorized persons in its requirements regarding safety precautions and scenario descriptions.

   - Proposals on achieving a balance between the legitimate public interest in information on the safety of industrial establishments and the potential security risks arising from such information.

In Italy, a project supported financially by the Italian Department of Civil Defence is in course, the aim of this project is the mapping of potential objects of terrorist attack in Italy. The study is carried out by the CONPRICI Consortium (CONsorzio interuniversitario per la PREVENZIONE et la Protezione dai Rischi Chimico Industriali), an association of seven Italian universities (Bologna, Messina, Politecnico di Milano, Napoli, Padova, Pisa, and Roma “La Sapienza”). The consortium is a scientific and technical consultant to the Italian Department of Civil Defence and the National Commission for the prevention of Major Hazards. The impact areas including data of population and vulnerable centers have been determined, the data has been implemented in a Geographical Information System (GIS) platform.

An evaluation of the risk of an installation against terrorist attacks, called "Attractiveness" of the target, has been carried out using a multi-criteria approach based on:

- Quantity and physical and chemical properties of dangerous substances in the site
- Characteristics of the plant and
- Vulnerability of the surroundings

Using this approach, sites at greatest risk (Highly Attractive) in Italy can be selected.

The project will have a profound and positive impact on all sectors when it is fully developed and implemented. It will help to define the facilities and operations of national and regional interest for the threat of terrorism, define standardized methods for analyzing consequences, vulnerabilities, and threats, and describe best industrial security practices. This study has provided the damage curves derived from incidental scenarios caused by terrorist attacks for the examined area. The effects map can constitute an important source of information for those have to enact specific emergency civil defence plans and also for those have to apply protection and/or mitigation measures for the exposed population.

3.2. DESCRIPTION OF INCIDENTAL SCENARIOS FROM TERRORIST ATTACKS

Recently, an approach (Lisi *et al*., 2007) has been proposed which allows the description of the sequence of events following a terrorist action. This approach has the aim of describing the overall scenario, defining the evolution of such actions starting from the initial cause and ending with the final catastrophic event; thus, the overall scenario can be studied considering it a sequence of simple steps. The proposed approach for the analysis of accidental events from terrorist attacks is outlined in the scheme shown in Figure 1. The study of the incidental scenarios caused by sabotage or terrorist attack can be made by considering these phenomena as primary events whose consequences hit a target. The hit target generates a secondary event which is able to widely

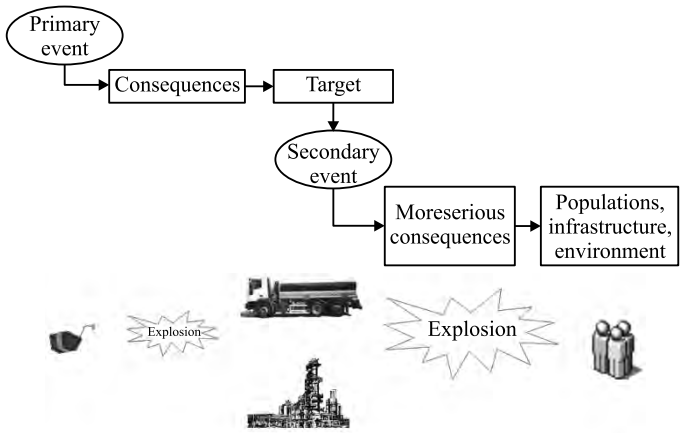

Figure 1. Evolution of terrorist actions.

spread the hazardous consequences of the first one. The primary event causes the release of a great amount of energy or toxic substances; thus, the final consequences cause serious effects to the population, infrastructure, and environment.

This approach allows the identification and characterization of the incidental scenarios due to terrorist attacks that is fundamental for the successive phase of the work in which the emergency measures will be identified. These measures must be developed on the basis of the type of incident and the magnitude of the risk.

3.3. QUANTITATIVE RISK ANALYSIS

Quantitative risk analysis including terrorist actions can be executed using the classical procedure adopted for chemical plants and the transport of dangerous goods (Advisory Committee on Dangerous Substances, 1991; CCPS, 1995); furthermore, this methodology must take into account also the scenarios caused by terrorist attacks and therefore, it must quantify the increased risk due to this type of event. This methodology must include the following phases:

- Frequency evaluation for the primary event
- Frequency evaluation for the overall scenario and
- Consequences evaluation for the overall scenario.

Taking advantage of the approach proposed in the previous paragraph the quantitative risk analysis can be simply executed.

3.4. FREQUENCY EVALUATION

The frequency evaluation involves the following phases: first, the frequency of the primary event should be estimated using data regarding this kind of event; then, it should be necessary to calculate the probability of success of the terrorist action and, thus, the frequency of the overall scenario could be defined according to the probability theory. Frequency evaluation is important because the phase of prevention is related to the determination of the likelihood that such events occur. Unfortunately, at present, these are still difficult to estimate, this represents a limit of the proposed approach (Lisi *et al*., 2007). As described above, the main problem is data collection regarding incidents caused by terrorist attacks to evaluate their frequency. Due to the complexity, of phenomenon, in terms of target type and geography of the areas, it appears to be very difficult to use classical safety methodologies and new techniques such as neural networks, fuzzy logic, etc. for this purpose.

A much more effective approach could be the definition of probability classes for the primary event relatively to the targets. Probability classes could be obtained on the basis of the available data, collected using governmental databases. Such classification, written up as tables, can be used together with the results of the consequences analysis of the incidental scenarios and would allow to define an index of risk. This index could be useful in the phases of emergency planning and location of the protection measures for the possible targets.

3.5. CONSEQUENCE ANALYSIS

The consequence analysis aims to quantify the negative impacts of the likely events, the consequences are normally determined in terms of the number of fatalities, although they could also be measured in terms of the number of injuries or the value of the property changed. The consequences estimation is necessary only for the secondary events because their effects are more severe compared to those due to the primary event.

The consequences estimation consists in the identification of the damage zones. The effects of the incidental events on the territory decrease in magnitude with increasing distance from the point of origin, based on the type of effects the territory is divided into the following zones:

- **"Zone of sure impact" (RED ZONE)**: characterized by a high percentage of human fatalities.
- **"Damage Zone" (ORANGE ZONE)**: characterized by possible serious and irreversible damage for people who do not take correct measures of self-protection.
- **"Attention Zone" (YELLOW ZONE)**: characterized by light damage also to vulnerable subjects and destabilization of normal life.

4. Case Study

The proposed methodology has been applied to a real but anonymous area. It is an urban area of high density of population, with a number of vulnerability centers distributed along the main road routes. Chemical plants and storage tanks are not present in this area, however, a large number of road-tankers transporting dangerous substances across the downtown; for this reason, the area is characterized by high level of risk.

The route under investigation is the connection between the main urban road and the highway exit; approximately, the traffic flow is 1,200 vehicles/ hour, this meaningfully increases the number of subjects exposed to potential incident scenarios. The high population density, the characteristics of the route (steep slopes), the presence of a great number of centers of vulnerability distributed along the route are some of the factors that make this area a potential target for terrorist attack.

4.1. IDENTIFICATION OF CRITICAL AREAS AND SCENARIOS DUE TO TERRORIST ACTIONS

The identification of the critical areas for terrorist actions can be made on the basis of a census of the substances and the targets.

- **Census of the substances** obtained on the basis of the type of hazard and of the quantities of dangerous products present in chemical plants, storage, and transport; it is possible to identify the worst substances that could be involved in an attack.

- **Census of the targets** obtained on the basis of the dangerous substances, the quantities, the operating conditions, and the territorial vulnerability, it is possible to identify all potential targets.

In order to mitigate the effects of the incidental scenarios, it is necessary to define the damage zones and to produce a map of the effects. In this study, attention has been focused on two types of incidents, toxic dispersion and explosion, since these can be considered the most catastrophic events.

According the census of dangerous substances and of targets, the critical areas are localized as shown in Figure 2. In this paper, the study has been focused on the study of the releases of chlorine and liquid fuels. The damage zones have been identified using the threshold values of Table 1 and are shown in Figure 3 and Figure 4.

The damage maps, supported by GIS tools, can constitute an important source of information to develop specific emergency plans.

Figure 2. Critical areas and localization of potential incidents.

On the basis of the threshold value of Table 1, Table 2 shows the number of vulnerable centers and people involved in a potential incident for each critical point identified above.

TABLE 1. Threshold values and damage zones

	Zone I (Zone of sure impact)	**Zone II (Damage zone)**	**Zone III (Attention zone)**
Concentration	$C \geq LC50$	$IDLH \leq C < LC50$	$C < IDLH$
Chlorine (dispersion)	High fatalities	Irreversible damage	No damage or light
Overpressure	$\Delta p \geq 0.3$ bar	$0.07 \leq \Delta p < 0.3$ bar	$\Delta p < 0.07$ bar
Liquid fuels (VCE)	High fatalities, structural damage	Fatalities and serious damage	No effects

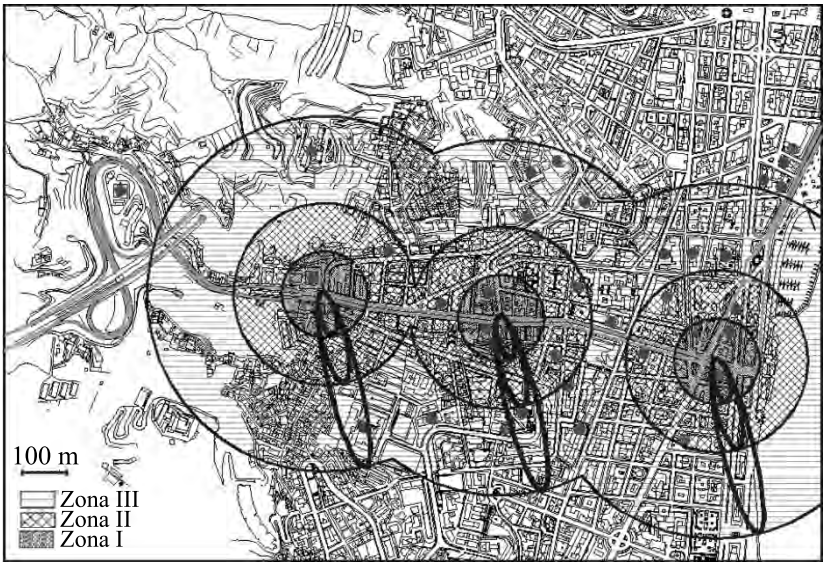

Figure 3. Effects of a catastrophic release of chlorine.

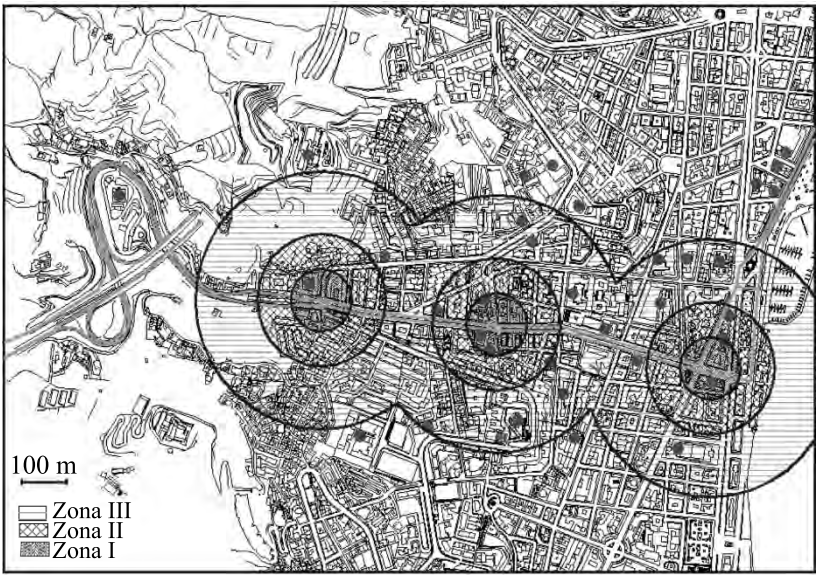

Figure 4. Effects of a catastrophic release of liquid fuels.

TABLE 2. Number of vulnerable centres and people involved (fatalities and injuries) in a potential incident.

	Point 1	**Point 2**	**Point 3**
Chlorine	8 vulnerable centers	22 vulnerable centers	13 vulnerable centers
toxic	17,997 people	25,179 people	9,852 people
dispersion			
Liquid fuels	2 vulnerable centers	12 vulnerable centers	6 vulnerable centers
VCE	8,948 people	12,378 people	1,551 people

4.2. GIS TOOL FOR EMERGENCY MANAGEMENT

The damage map can constitute an important source of information to develop specific emergency civil defence plans and to apply protection and/or mitigation measures for the exposed population. A very efficient tool is represented by the implementation of the map of the consequences on a GIS platform. Two examples of this kind of application are reported.

Figure 5 shows the scheme of car bomb containing propane and gasoline similar to those found in central London in June 2007.

Figure 6 shows the results of a simulation of the consequence of a fireball generated by the car bombs in the case of complete success of the event. The map of the consequences of the attack is shown in Figure 7. The circle represents the area in which a high probability of fatalities is observed. The GIS interface permits an immediate visualization of the target area including the presence of vulnerable centers.

Using a GIS tool developed in our laboratory, it is possible to have a dynamic description of the time evolution of the plume generated by the incident and as a consequence the determination of damage area as

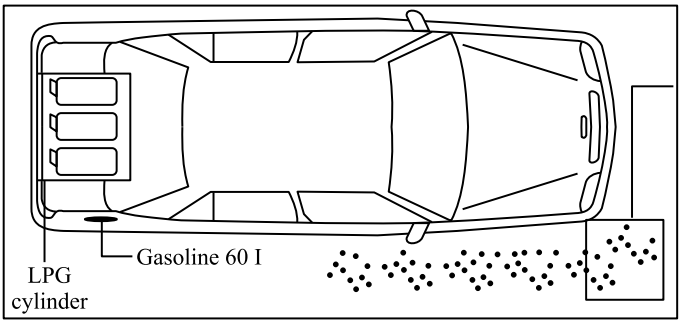

Figure 5. Scheme of a car bomb.

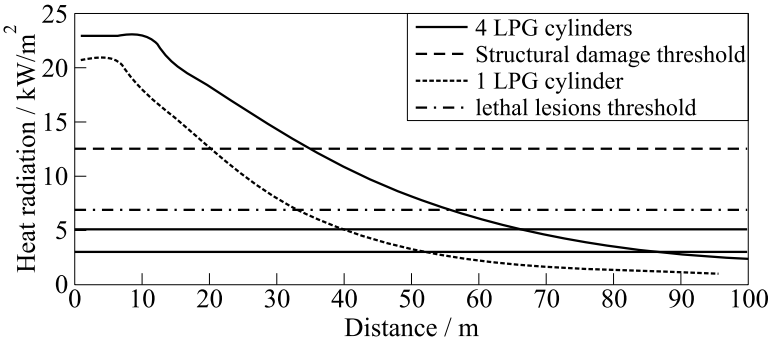

Figure 6. Consequence of a fireball generated by the car bomb.

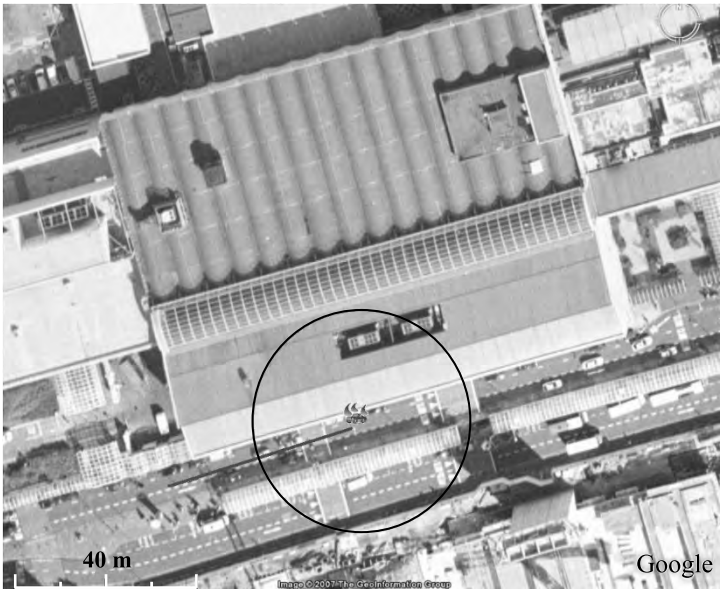

Figure 7. Map of the consequences of the attack.

a function of time. This kind of dynamic effects map can constitute an important source of information for those who have to enact specific emergency civil defence plans and, moreover, also for those who have to apply protection and/or mitigation measures for the exposed population. Figure 8 shows an image of the dynamic simulation of a catastrophic release of chlorine due to the explosion of a road tanker in an urban area.

5. Concluding Remarks

The problem considered in this paper is of great interest, because in recent years, the areas susceptible to terrorist attacks have been widening. The methodology applied in this work has the aim of outlining the scenario associated with a terrorist attack or sabotage. The case study is a city characterized by the transport of large quantities of hazardous materials. Even if it may not be the principal object of a terrorist attack, this kind of city has all the characteristics of a potential target in terms

Figure 8. An image of the dynamic simulation.

of territorial vulnerability. The high number of road and rail tankers transporting dangerous substances in the urban area and the presence of numerous vulnerable centers along the main transportation routes are typical of areas subject to terrorist attacks.

This study has provided the damage curves that would derive from incidental scenarios caused by terrorist attacks for the examined area. The effects map can constitute an important source of information for those who have to enact specific emergency plans of civil defence and, moreover, also for those who have to apply protection and/or mitigation measures for the exposed population. The damage curves also allow considerations to be made regarding possible alternatives in the transport of dangerous substances using different routes at different times of the day.

In particular in this study, the continuous monitoring of road/rail tankers and the typologies of substances crossing the urban areas has been suggested. This is possible using appropriate control systems located at the motorway exits and the ferry terminals or at critical points along the main routes used for the transport of dangerous goods.

Finally, emergency plans must be updated and performed taking into account the vulnerability of the territory and they must include the

definition of services, procedures, and emergency resources. Emergency plans have to be periodically tested in order to verify their validity.

The methodology applied needs to be implemented in order to improve the use of safety methodology also for security problems. In this work, the definition of probability classes for the primary event relative to the targets has been proposed. Combined with the conesquences results, this permits the identification of risk indices. These indices could be useful in emergency planning and for the location of the protection measures for the possible targets.

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MICROBIAL AGENTS AND ACTIVITIES TO INTERFERE WITH GROUNDWATER QUALITY

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Abstract: Deterioration of groundwater quality either an accidental or intentional one may cause a severe harm to the affected human population. Different pathogenic bacteria as well as viruses are capable of surviving rather long upon physical-chemical conditions that govern in a groundwater aquifer, and also they could be transported long distances from the site of contamination. The activity of natural bacterial predators such as *Bdellovibrio* sp. might fail under an ambient temperature of about 10°C. Since bacteria autochthonous to groundwater aquifer have been found resistant to various chemical contaminants, a natural attenuation of polluted groundwater resources might be possible, though time consuming. In some groundwater aquifers, humic substances occur that can be formed *in situ* or released from a fossil wood deposited in the aquifer. These substances are capable of binding, transporting and releasing again of chemical pollutants. Due to its high importance as drinking water resource, groundwater deserves a priority protection against bacteriological and chemical contamination.

Keywords: groundwater contamination; micro organisms; chemicals; humic substances

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1. Introduction

Groundwater may represent less than 1% of all water on the Earth but simultaneously, it stands for some 90% of fresh water reserves (Stetzenbach *et al*., 1986; Coates and Achenbach, 2002). In Germany, about 50% of drinking water originates from groundwater resources (Schleyer and Kerndorff, 1992). Similar was true for the former Czechoslovakia, now the Czech Re-public and the Slovak Republic, where some 45% of drinking water supply was covered by groundwater, with a long-term tendency to enhance this percentage (Filip, 1989).

According to Bitton and Gerba (1984) over 100 million Americans rely on groundwater for drinking water purposes, and in rural areas up to 95% of the water used is groundwater. For this reason, a public concern is growing as to the health hazard caused by an accidental or intentional pollution of groundwater resources.

Czech scientists ever devoted a great attention to research and education dealing with different aspects of groundwater quality and related management. Pelikan (1983) stressed the topic extensively in a textbook. In another volume, Melioris *et al.* (1986) elucidated the groundwater management, and described different techniques for exploration and utilization of groundwater resources.

2. Health Relevant Microorganisms in Groundwater

Groundwater aquifers naturally harbor microbial communities the specific composition of which co-defines the water quality and its suitability for human consumption and other uses. These communities can be divided into (i) stygobionta, i.e., autochthonous microbes obligatory inhabiting groundwater aquifer; (ii) stygophilic microbes that preferentially inhabit groundwater but are capable of living in a surface water as well, and (iii) stygoxenic microbes, i.e., allochthonous ones, that may enter groundwater aquifer accidentally, or could be released intentionally (Pelikan 1983). The average microbial counts in a groundwater environment are presented in Table 1.

In Figure 1 a picture is reproduced of bacteria adhearing to a clay particle.

TABLE 1. Average counts of bacteria in a groundwater environment. (From Pelikan, 1983).

Sample	Counts of bacteria ml^{-1} (g^{-1})
Groundwater pumped	10^3–10^5
Groundwater ladled	10^2–10^4
Mud from a groundwater well	10^4–10^7
Sediment from a groundwater aquifer	10^5–10^7

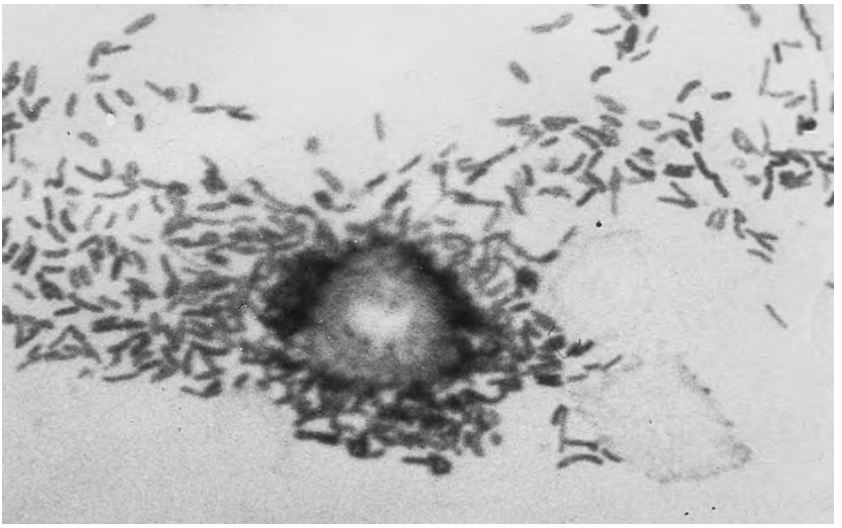

Figure 1. Bacteria adhering to a clay particle. (Photo by Z. Filip.)

In general, microorganisms in groundwater are capable of (i) removal organic carbon compounds that impart odor and flavor to drinking water; (ii) solving minerals, with an increase in dissolved solids and alteration of aquifer permeability; and (iii) catalyzing reaction that lead to an elevated concentration of undesirable compounds, such as ferrous iron and hydrogen sulfide (Coates and Achenbach, 2002). In dependence on the aquifer depth, the microbial metabolism includes aerobic, facultative anaerobic, and obligatory anaerobic processes in the underground.

An improper treatment and usage in agriculture of manure, municipal wastewater, sewage sludge and solid wastes, can lead to contamination of groundwater aquifers with pathogenic or facultative pathogenic microorganisms. Czech scientists recognized this as early as in 1877

according to Pelikan (1983) and they required regular bacteriological water testing. According to Gerba (1985) several surveys performed in the USA have indicated that rainfall and the well depth may have impact on the microbial quality of groundwater. In a rural region of Texas, e.g., practically all wells with depth of 15 m or less were found positive in the contamination by either fecal coliform or fecal streptococci. El-Zanfaly and Shabaan (1988) documented a significant level of bacterial pollution in groundwater samples drawn from 15 wells in Egypt, the depth of which ranged from 45 to 95 m. Total or fecal coliforms, and clostridia were detected in 92%, 55%, and 45% of samples, respectively. Recently, the American Academy of Microbiology strongly recommended to reconsider available knowledge on possible misuse of microorganisms, and to develop novel methods to identify and control pathogenic bacteria that might be used in a bio-attack (Keim, 2003).

For the sake of drinking water security it is very important to obtain data on the survival and transportation of potential pathogenic agents in groundwater. Pelikan (1983) reported on coliform bacteria as surviving in a broad range between 40 and 1,000 days, and being transported up to 1,200 m. In our laboratory, we checked the survival of different health relevant bacteria in groundwater samples. The species used, their origin and sanitary importance are listed in Table 2.

TABLE 2. The bacteria under testing and their sanitary importance.

Bacteria	Sanitary importance
Escherichia coli	Enteritis; local infections
Salmonella typhimurium	Enteritis; typhoid fever; food poisoning
Pseudomonas aeruginosa	Otitis; urogenital inflammation; skin gangrene
Yersinia enterocolitica	Diarrhoea; appendicitis; septaemia
Staphyloccocus aureus	Skin inflammation; enteritoxin formation
Streptococcus faecalis	Nonspecific infections
Bacillus cereus	Nonspecific food poisoning; infections in animals
Bacillus megaterium	Food spoilage
Clostridium perfringe	Gasoedema; tissue necrosis; enterotoxin formation; food poisoning

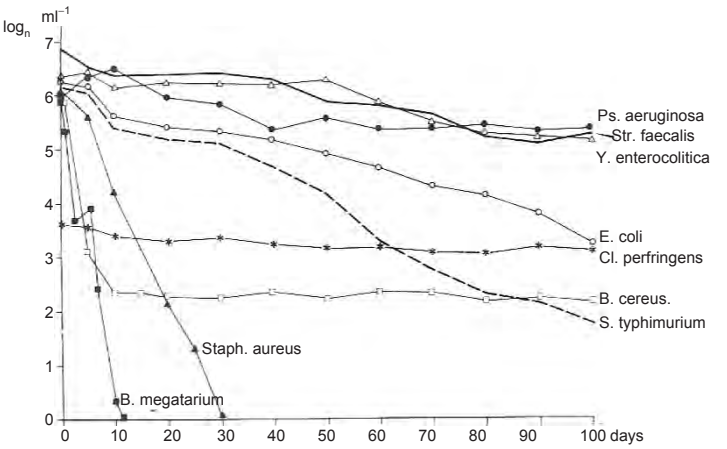

Figure 2. Survival of some pathogenic and facultative pathogenic bacteria in groundwater. (From: Filip *et al*., 1988)

For the experiments, groundwater was obtained from a 140 m deep well, and kept at 10°C ± 1°C. Some experimental microcosms contained sand that was collected from a Pleistocene groundwater aquifer. In this way, conditions near to a porous aquifer have been simulated. More information about our methodical approach, and the analytical details, can be found elsewhere (Filip *et al*., 1988).

The curves in Figure 2 indicate that although no apparent multiplication occurred under experimental conditions, bacteria mainly survived at rather high cell-concentrations for a period of 100 days. Only *B. cereus*, *B. megaterium* and *S. aureus* were strongly reduced, i.e., by 2–6 log, within 10 days. *B. megaterium* was completely eliminated after 12 days, and after 30 days *S. aureus* was no more detected. The colony counts of *B. cereus* and similarly those of *C. perfringens* were strongly reduced during the first 10 days but later they remained almost stable, perhaps, due to the formation of resistant spores. *B. megaterium*, also a spore-forming bacterium, apparently did not form spores in groundwater microcosms. Some other bacteria under testing, e.g., *S. faecalis*, *P. aeruginosa*, and *Y. enterocolitica*, survived up to 50 days upon a reduction less than 90%. The counts of *E. coli* and *S. typhimurium* were reduced by 4 log, i.e., 99.99%. In the presence of sand from a groundwater aquifer, the survival of some bacteria was prolonged (not shown).

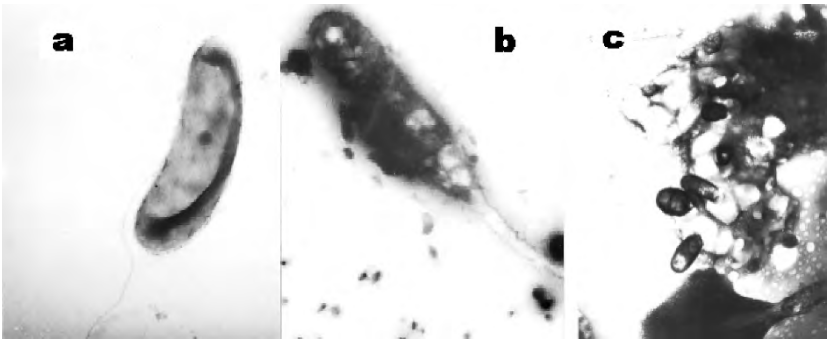

Figure 3. Bdellovibrio sp.: (a) A strongly magnified single cell; (b) Individual bdellovibrios (very small cells) attacking a bacterium; (c) Destroyed bacterial cell releasing bdellovibrios. (Photo by R. Smed-Hildmann/Z. Filip)

In summary, the test bacteria inoculated into groundwater microcosms remained mainly viable and detectable in numbers between 10^2 and 10^6 ml^{-1}. In view of these experimental results, a "50 Days Die Off Limit" for pathogenic bacteria, a presumption of the groundwater safety still advocated in Germany (Knorr, 1951), and which is widely respected in practice, seems somewhat weakly founded.

In many natural and polluted aquatic environments, the existence of bdellovibrios have been documented, and their role as a predator in nutrient-impoverished sites was investigated (Rittenberg, 1979). These organisms exist as a small (ca. 0.3 × 1.5 μm) highly motile prokaryotic cell which is incapable of independent growth and reproduction. For reproduction to occur, bdellovibrio collides with, and attaches to a gram-negative bacterium. Then it penetrates through the cell membrane, and multiplies while the target bacterium dies. Since many bacteria recognized as groundwater contaminants belong to the gram-negative group, we wished to establish, whether bdellovibrios are to be considered as a serious factor to control the spread of health relevant bacteria in groundwater. *Bdellovibrio* sp. that was used in our experiments was capable of attacking *E. coli* (Figure 3). However, as shown in Figure 4, its growth activity occurred only in a temperature range between 25–30°C. Thus, in a groundwater aquifer with ambient temperature of about 10°C, bdellovibrios apparently do not play a role as the factor to control pathogenic bacteria (Filip *et al*., 1991).

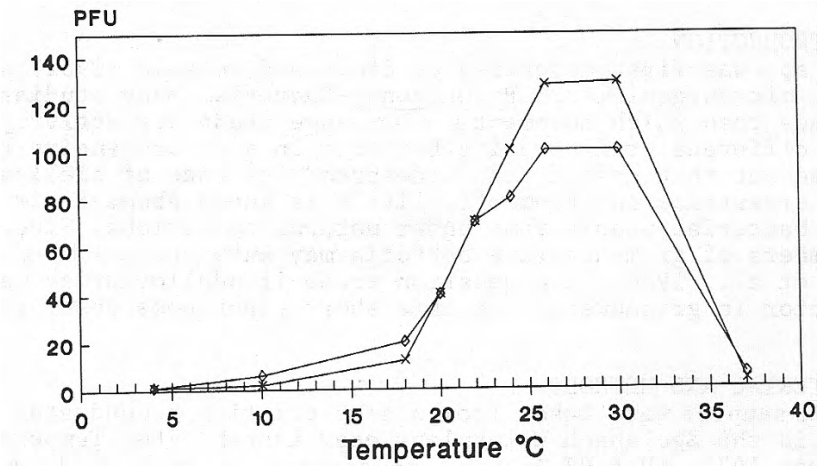

Figure 4. Effect of temperature on predatory activity of Bdellovibrio sp. against E. coli grown on nutrient agar (PFU = plaque forming unit). (From Filip *et al*., 1991)

Several authors from Russia and Eastern European countries studied the behavior of sanitary important microorganisms in groundwater, and in a comprehensive report, Filip (1989) summarized their results as follows: (i) in a sandy or shell-calcareous groundwater aquifer health important bacteria survive from 30 to 400 days; (ii) simultaneous contamination of groundwater aquifer with phenols or mineral oil derivates does not effect the survival of the sanitary important bacteria but sometimes it stimulates the growth of autochthonous saprophytic microbes; and (iii) in addition to their ability to survive, the transportation of pathogenic bacteria in groundwater is of importance for the sanitary safety of groundwater. The following average radii of bacterial spread should be taken into account: (i) In aquifer composed of a fine sand (grain size < 2 mm) about 30–40 m; (ii) in aquifer composed of coarse sand (grain size 2–4 mm) up to 200 m; and (iii) in a gravel and karstic aquifer up to 1,000 m.

More than 100 types of enteric viruses are considered pathogenic to man, and the ingestion of only a single virus particle can lead to infection in a certain proportion of susceptible people. A number of outbreaks of water born diseases is caused by viruses (Filip, 1983). In the USA, e.g., viruses were identified as the causative agent in 12% of the waterborne disease outbreaks between 1946 and 1980 (Lippy and Waltrip, 1984). Viruses can be transported for great distances and persist for months in a groundwater aquifer (WHO Report, 1979). Using a

bacteriophage as a model, Yates and Yates (1988) calculated setback distances between 15 and 150 m to achieve a safe concentration (7 log) decrease in groundwater. In our investigations on the spread of enteroviruses in a sandy soil long-term irrigated with wastewater, however, we detected the presence of viruses at a maximum soil depth of 2 m (Filip *et al*., 1983).

3. Relationship Between Organic Pollutants and Microorganisms in Groundwater

Beside of microbial agents, various chemical compounds may cause severe contaminations to groundwater. In many industrial countries halogenated hydrocarbons play an important role (Hagendorf and Leschber, 1990). In a large-scale assessment which included analyses of about 3,500 groundwater wells in the USA, Zogorski *et al*. (2006) identified 55 volatile organic compounds. Trihalomethanes, which are widely used as solvents belonged among the most frequently detected contaminants. Eight individual compounds such as trichloroethene, perchloroethene, and 1,1-dichloroethene were found at concentrations of health concern in domestic and public wells.

For many reasons, natural attenuation might represents the only realistic alternative to clean up a contaminated aquifer (McCarty and Ellis, 2002; Reible and Demnerova, 2002). An essential condition for applying this simple technology is the resistance of groundwater microorganisms against chemical contaminants. Neither the growth of microorganisms nor their enzymatic activities must be inhibited by the contaminant. In order to test this presumption, we performed laboratory experiments using a complex population of microorganisms from a deep pristine groundwater aquifer, and applying different chemicals known as groundwater contaminants. Methodical details have been published elsewhere (Filip and Demnerova, 2006). In Table 2 and Table 3, the Minimum Effect Concentrations (MEC) are shown for a 1- or 42-day exposure, and which reflect a 50 % inhibition rate (EC_{50}) obtained in the most sensitive tests. Apparently, microorganisms were resistant against high concentrations of chlorinated aliphatic hydrocarbons (Table 3). In both short- and long-term tests similar results were obtained. Biologically driven dehalorespiration and a hydrolytic degradation of some halogenated compounds may occur according to

TABLE 3. Effects of chlorinated aliphatic hydrocarbons on groundwater microorganisms (From Filip and Demnerova, 2006).

Compound	Solubility	MEC (1 day)	MEC (42 days)
Dichloromethane	16,000	3,000[a]	
Trichloromethane	9,000	300[a]	1,000
Tetrachloromethane	800	500[a,b]	
1,1,1-Trichloroethane	500	310[a]	
1,1,2-Trichlorotrifluoroethane	170	n.e.	n.e.
1,2-trans-Dichloroethene	600	370[a,b]	n.e.
Trichloroethene	1,100	300[a]	300
Tetrachloroethene	150	94[a,b]	94
1,2-Dichloropropane	2,700	1,700[a]	
1,3-Dichloropropene	2,700	100[a]	100
Hexachlorobutadien	2	1[b]	
α-Hexachlorocyclohexane	1.4	n.e.	
β-Hexachlorocyclohexane	0.24	0.15[b]	
γ-Hexachlorocyclohexane	1.9	n.e.	

Values in ppm; n.e. = no effect
[a]Value obtained in ATP test.
[b]Value obtained in dehydrogenase test.

TABLE 4. Effects of anilines and phenols on groundwater microorganisms (From Filip and Demnerova, 2006).

Compound	Solubility	MEC (1 day)	MEC (42 days)
N-Methylalanine	30,000	300[a]	<30
N,N,-Dimethylalanine	1,000	620[a,b]	620
2,4-Dimethylalanine	1,000	100[a,b]	
Phenol	82,000	30[a]	
2,4-Dichlorophenol	4,500	10[b]	
2,4,5-Trichlorophenol	2,000	0.3[a]	>3
Pentachlorophenol	2,000	0.3[b]	3

Values in ppm; for [a,b] see Table 3

results obtained under laboratory conditions (Holmes *et al*., 1998; Mitchell and Fox 2002). Nevertheless, many indications exist that *in situ* the natural attenuation is not very effective, and it fails to prevent pollutants from their spreading in the subsurface.

Data in Table 4 show that anilines exert toxic effects on groundwater microorganisms already by concentration as low as 1% of a full water saturation. Even more, trichlorophenol and pentachlorophenol exhibited the strongest (short-term) toxicity of all chemicals under testing. However, the results obtained after 42 days indicate that, some adaptation of microorganisms to the elevated concentration of chemicals may also occur.

4. Humic Substances as a Factor Affecting the Behavior of Pollutants in Groundwater

Usually, humic substances represent both quantitatively and quailtatively most important organic matter in pristine groundwater, and they are of hygienic relevance for the drinking water quality (Thurman, 1985; Filip and Smed-Hildmann, 1991).

As to their origin, humic substances in groundwater may arise from simple organic compounds or from decaying organic matter entering the underground from a sanitary landfill (Filip and Smed-Hildmann, 1988). In some groundwater catchments in Germany, high concentration of humic substances appears (Kölle, 1993) the origin of which could be connected with a deep fossil-wood deposit (Filip and Smed-Hildmann, 1992).

Groundwater humic substances were found capable of binding Ca^{2+}, Cu^{2+}, Mg^{2+}, Al^{3+} and Fe^{3+} cations. Based on ^{13}C NMR and FTIR investigations Alberts *et al.* (1992) postulated that in humic acids, these cations are predominantly associated with carboxylic structural groups. Artinger *et al.* (2000) demonstrated a migration behavior of the actinide elements U, Np and Am bound on humic colloid to be faster than the groundwater flow velocity in a subsurface aquifer.

Concerning the interactions between humic material and organic water pollutants, the dissolved humic substances have been reported as being responsible for the leaching of polycyclic aromatic hydrocarbons into an aqueous phase in a polluted site. The solubility of carbazole, e.g., in groundwater was increased by 108% in the presence of 100 mg L^{-1} humic acid (Lassen and Carlsen, 1997). Payer *et al.* (1997) concluded from experimental data obtained with 16 volatile organic compounds that the pollutants can bind with considerable forces to either hydrophobic or hydrophilic sites both at the surface, and in structural cavities of colloidal humic particles. The stronger the inter-

action forces, the stronger environmental effects of the pollutants can be expected.

5. Conclusions

Groundwater may become easily contaminated by pathogenic bacteria and also by different chemicals. Both type of contaminants are capable of a long-term persistence and, in addition, they can spread in the underground over distances. In these respect a possible risk for groundwater resources from activities of terrorists represent a severe threat for the drinking water supply. Since remediation of aquifers appears very difficult for many reasons, an effective protection of groundwater resources from contamination should be warranted.

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PRELIMINARY RESULTS OF A RISK ASSESSMENT STUDY FOR URANIUM CONTAMINATION IN CENTRAL PORTUGAL

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Abstract: The Central region of Portugal contains a large number of U-mineral occurrences and 60 abandoned uranium mines exploited since 1907. The U mineralisation is mainly hosted in granitic rocks, naturally radioactive. Thus, the objective of this study is to evaluate the risk for population of the mining explorations and unexploited mineralisations. The study consisted of two units approach, one, where specific regional indicators: land use, lithology, natural gamma radiation, geoaccumulation index of uranium in stream sediments, distance from uranium mines to land use categories, and a classification of mines based on: type of exploitation, volume of waste, leaching and acid water presence, are used as hazard potential. Vulnerability was considered as a "number of inhabitants per water system." Another approach uses municipality as unit (NUTS IV) where the hazard potential is characterised by the number of mines per municipality, water system per municipality, inhabitants per water system, and the classification of mines. The vulnerability was divided in damage potential and coping capacity, damage potential is regional gross domestic product (GDP)

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per capita and population density and coping capacity is number of doctors per 1,000 inhabitants and national GDP per capita. In the first approach, the areas enriched are bigger than the mining areas, meaning that natural radioactivity can be important in this hazard characterization. In the second approach, the higher risk municipalities have open pit uranium mines with acid mine drainage, high volumes of waste materials and medium population density, GDP per capita and less doctors per 1,000 inhabitants. These municipalities are Gouveia, Guarda, Mangualde. The results are conditioned by the available data to introduce in the study, specially the vulnerability data that may change with time.

Keywords: Risk assessment; uranium contamination; indicators; hazard; vulnerability

1. Introduction

Uranium and its decay products vary widely as a result of geology and also as a result of mining or nuclear industry. For instance, in UK, only 0.1% of ionising radioactivity is related to nuclear industry, whereas that from natural radioactivity is approximately 85% (Plant *et al*., 2003). Uranium released to the environment may be present in different physical-chemical forms, ranging from ionic species to particles and fragments. Its uptake by plants and absorption by animals occurs mostly through water solutions (Ibrahim & Whicker, 1992). Thus, in the environment, water is the most vulnerable media and the interaction waters-mineral phases containing uranium, especially when secondary phases of uranium are present, is the key to a risk assessment in this case. Uranium species stable with water are U(IV) and U(VI) oxidation states, and under reduction conditions U(IV) is insoluble. The solubility and mobility of uranium in superficial waters of rivers increases at low pH and specially, in oxic conditions forming uranyl ion easily forming complexes with carbonates, phosphates, hydroxide, and fluoride (Chabaux *et al*., 2003). Various studies tried to model the range of U isotopes in groundwater considering the uranium nuclide and the decay chain as retardation factors. These studies can also be analogue to model migration of U in low level radioactive

waste in the environment. There are different approaches to this modeling but all are based on relation between nuclides by radioactive decay and processes of input by weathering and recoil into groundwater and interactions with the aquifer host rock surfaces by sorption and precipitation (Porcelli and Swarzenski, 2003).

Risk assessment indicators according to the European Environmental Agency (EEA) can be used to express the condition of complex systems by summarizing the complex into a manageable and understandable message. Each indicator by itself tells a story as part of the whole, and only by combining indicators it is possible to gain a complex view. Indicators can express hazard potential, when potential risk is involved and vulnerability as a degree of fragility to a potential hazard. Vulnerability can also be divided in damage potential when a certain phenomena can contribute to an hazard and coping capacity when ability to resist or prepare the response to the hazard is measured (Schmidt-Thomé and Jarva, 2001).

In Portugal, two main uranium provinces are known – one of them is in the Central Portugal, related with variscan granites, especially the post-orogenic monzonitic and biotitic-moscovitic porphyritic granites, intruded in the "Complexo Xisto Grauváquico" and their fault system related to the final variscan orogenic tensions (Cavaca, 1968). In this province, where 60 mines were exploited for U and Ra since 1907, INETI database have registered 456 U-mineral occurrences.

The objective of this study is to use two different methodology approaches to determine the potential uranium contamination risk of exposure to humans, in Central Portugal related to the uranium mines and mineralisations.

2. Site Description

The Central Region of Portugal occupies an area of 23,666 km^2 (25.7% of Portugal mainland) and includes 78 municipalities. The population totals almost 1.8 million inhabitants (17.2% of the total). This region holds important soil potential for agricultural purposes, ornamental rock resources particularly granite, which is capable of being used in many industrial and commercial activities. Additionally, the region is characterized by an extensive forest area, particularly of pine

and eucalyptus, representing 1/3 of the Portuguese forestry area (Schmidt-Thomé and Jarva, 2001).

The region is traversed by the main mountain chain in Portugal, which culminates in the "Serra da Estrela" mountain (1,991 m). The "Orla Ocidental" occupies the Central Region of Portugal in the coastal region and consists of a sedimentary belt comprising Triassic to Quarternary formations. The Central Iberian Zone, Southwest sector and part of the Douro-Beiras sector corresponds to the older Proterozoic formations up to the Carboniferous. Within the Central Iberian Zone are included several varieties of granitic rocks that host the majority of the uranium occurrences such as Late Hercynian monzonitic granites (Oliveira *et al*., 1992).

Uranium exploitation existed in the Central Region of Portugal since 1907 (discovery of the Urgeiriça ore) until 2001 with the closure of the Sevilha and Quinta do Bispo Mines. A total of 456 mineral occurrences were identified and evaluated during exploration work and 60 mines were exploited (45 open-cast; 15 underground). Hence, these numbers justify the selection of this hazard "Uranium mine contamination" (Batista, 2003).

3. Methodology

3.1. INDICATORS

3.1.1. *First Methodology Approach*

To the first approach where the unit of work is the pixel definition of 100 × 100 m the following indicators to characterize the hazard potential were used: land use (Direcção Geral das Florestas), lithology (Atlas do Ambiente Digital) and "natural gamma ray exposure rate" (Torres and Grasty, 1993), "distance of uranium mines from land use categories" (SIORMINP database); "the uranium concentration in stream sediments" (Ferreira, 2000), this indicator was represented as "Geo-accumulation Index" (Müller, 1979). Mine classification by three categories of hazard potential. The "water systems per municipality" (Qualidade da Água de Consumo Humano, 2000) and "inhabitants per water system" (Qualidade da Água de Consumo Humano, 2000) characterize the vulnerability and were chosen because they represent the potential effect on human lives by water consumption.

Classification factors to compose the risk map are considered in three classes: (i) low risk factor (blue), (ii) medium risk factor (light green), and (iii) high risk factor (red).

In the land use indicator, high sensitivity areas (high risk factor) to uranium mine contamination were determined by the agriculture areas and interior waters body areas (e.g., lakes, dams) and social areas, medium sensitivity was determined by the forest areas, and lower sensitivity areas were determined by the unproductive and uncultivated areas.

Three classes were obtained for lithology classification: low risk class (limestones, sandstones, silts, clays), medium risk class (shales and quartzites), and high-risk class (granitic rocks).

The indicator "distance from the uranium mines and mineral occurrences to the land use categories" was obtained from the location of the uranium mines and the location of the known mineral occurrences (456) to the land use categories, such as agriculture, interior water bodies and social areas and forest, uncultivated and unproductive areas. The extreme situation of higher risk occurs with a distance of 500 m from mines and mineral occurrences to agricultural and interior waters or social land uses while the lowest risk occurs in a situation of 50-km distance from the mines and mineral occurrences to the unproductive and uncultivated land use categories. The factor map is obtainned by the calculation of land use categories multiplied by 10,000 and divided by the distance from the mines and mineral occurrences.

The Geoaccumulation index indicator (Müller, 1979) was defined as:

$$I_{geo} = \log_2 C_n / B_n \times 1.5,$$

where C_n is the chemical element concentration n in fine-grained sediments of the present sediments results; B_n is the geochemical background from clay fraction sediments (average value in clays); and the 1.5 factor was calculated by the authors to prevent lithological changes in the background values.

These results were classified in 7 classes represented in Table 1.

Natural gamma ray is represented in exposure rate and with standard deviation intervals. One and two standard deviations below the average were considered as the lowest risk, the average and one standard

TABLE 1. Classification of the geoaccumulation index.

I_{geo}(class)	Geoaccumulation index	Degree of pollution
6	>5	Very strong pollution
5	>4–5	Strong to very strong pollution
4	>3–4	Strong pollution
3	>2–3	Moderated to strong pollution
2	>1–2	Moderate pollution
1	>0–1	Weak to moderate pollution
0	<0	Absent to weak pollution

TABLE 2. Classification of exploited mines.

Type of waste	Class	Type of mine	Class
Waste rock ≤ 20,000 t	1	Open pit	3
Waste rock > 20,000 t	1	Underground	1
Waste rock > 1,000,000 t	2	Both works	3
Poor ore ≤ 2,000 t	3		
Poor ore > 2,000 t	3		
Poor ore > 1,000,000 t	3		
Rejected from treat ≤ 2,000 t	2		
Rejected from treat > 2,000 t	3		
Rejected from treat >1,000,000 t	3		
Leaching	Class	Acid water	Class
Yes	3	Yes	3
No	1	No	1

deviation above were considered as the medium risk and the two and three standard deviations above the average were considered as the highest risk. This parameter is measured as the quartile of exposure rate.

Mine classification indicator was based in three categories. The classification was based in volume and type of waste, type of exploitation, leaching and presence of acid mine drainage, where poor ore and material rejected from treatment were considered as higher hazard potential as well as higher volumes. Underground mining works were considered as lower hazard potential than open pit works and the presence of leaching and acid mine drainage are also considered as higher hazard potential (Table 2).

The indicator "water systems per municipality" (Qualidade da Água de Consumo Humano, 2000) was considered relevant because small systems for small villages are more vulnerable to contamination related to older uranium mining activities because treatment in these small systems does not include sufficient parameters. More systems per municipality mean smaller systems per municipalities.

The indicator "inhabitants per water system" (Qualidade da Água de Consumo Humano, 2000) was considered important due to the fact that water for human consumption is at the highest risk for radioactivity contamination. This information was obtained only for the groups of systems per municipality. However, in future, it should be developed with more detailed information. Water system is, in this case, the source and the net system of supply of water to inhabitants.

3.1.2. *Second Methodology Approach*

In the second approach of the study, the unit was the municipality (NUTS IV) and the indicators to characterize the hazard potential were umber of mines per municipality, water system per municipality, inhabitants per water system, and mine classification (volume and type of waste, type of exploittation and acid mine drainage, and leaching).

The number of mines per municipality was an indicator considered because if a municipality had a higher density of uranium mines or mineralisations was most probably better exposed to the hazard contamination of uranium.

3.2. CLASSIFICATION

3.2.1. *First Methodology Approach*

In the first case, the classification was made by "Land use categories × 10,000/Distance to uranium mines and mineralisations" and by the addition of the geoaccumulation index map, "water system per municipality" and "inhabitants per water system," lithology and natural gamma radiation exposure (Figure 1).

Added to the previous mentioned synthesis map, the classificati on of the mines based in the volumes of waste and types of waste rocks since the chemical reactions are different if we consider a volume of waste rock and the same volume of waste, rejected from the mining

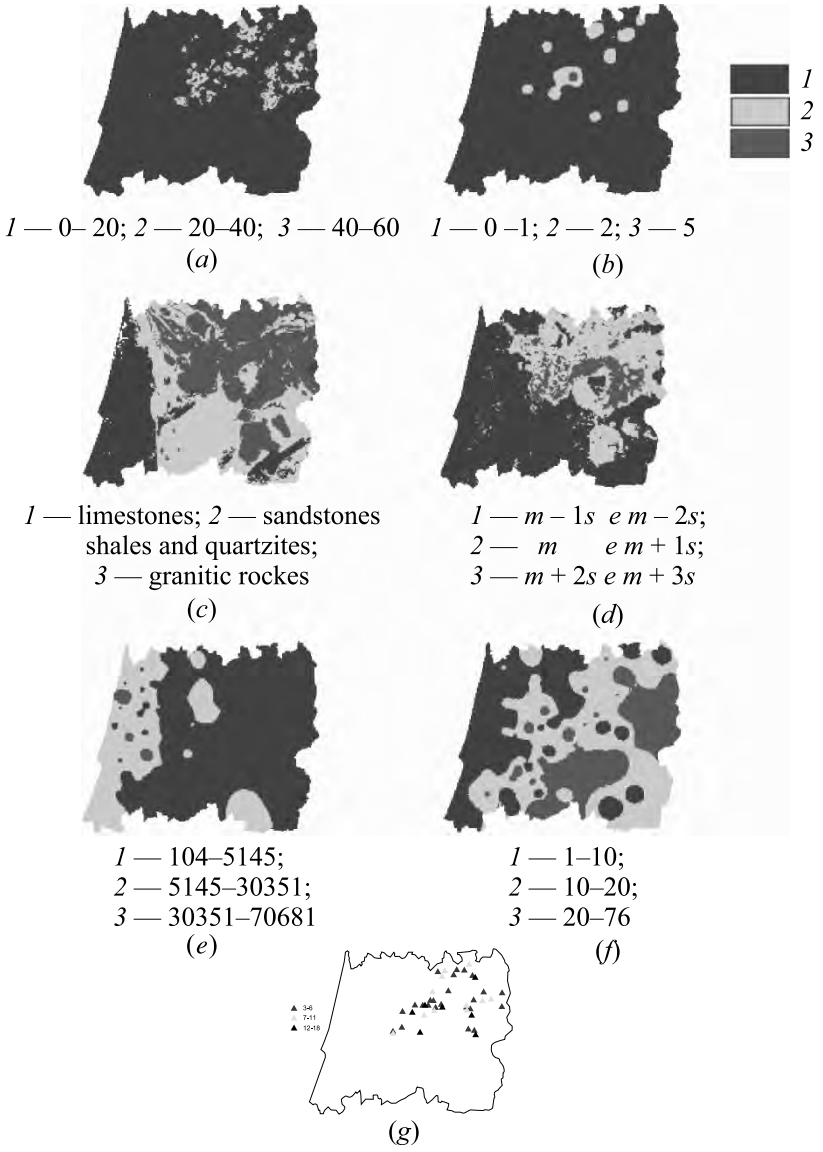

Figure 1. Classification maps of the hazard "uranium mines contamination": (*a*) distance from uranium mines and mineralizations to land use categories; (*b*) geoaccumulation index; (*c*) lithology; (*d*) natural gamma ray exposure rate; (*e*) people per water system per region; (*f*) water system per region; and (*g*) three mine classes.

treatment plant, or poor ore, where still remains considerable concentrations of uranium and uranium decay products. The mine classifications were made by type of exploitation, volume and type of waste, leaching practice and acid mine drainage.

The risk map is represented in Figure 2 and is the result of three synthesis maps. Lithology + Gamma Ray Exposure, Distance from uranium mines to land use categories + U Geoaccumulation Index in stream sediments and Number of water systems per municipality + Inhabitants per water system and above that map, the classification of mines.

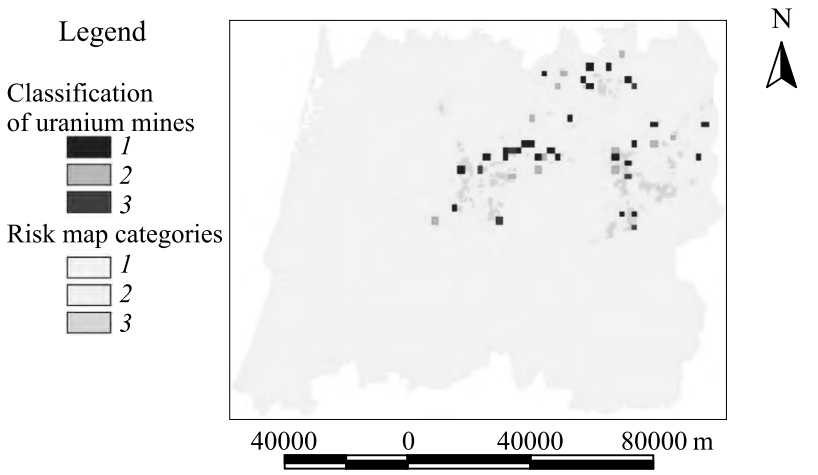

Figure 2. Hazard potential map "uranium mine contamination" in Central region of Portugal.

3.2.2. *Second Methodology Approach*

In the second approach, the classification was made with a smaller number of indicators that were composed in an aggregated hazard potential map. The number of mines and mineralisations per municipality was divided in three classes, one less than 10, another between 10 and 30 mines, and the last one higher than 30 mines. The same criterion was applied for the number of water systems per municipality. The number of inhabitants per water system was divided in lower than 5,000 inhabitants per water system, medium between 5,000 and 20,000 inhabitants, and higher class higher than 20,000 inhabitants.

Mine classification was divided in three classes, low considered underground mining, waste volumes less or equal to 2,000 t and waste rock materials, no leaching and no acid water, higher class when the mine is an open pit or both (also underground), wastes are higher than 100,000 t, waste materials are poor ore or wastes from mining treatment plant, and with leaching of acid water (Figure 3).

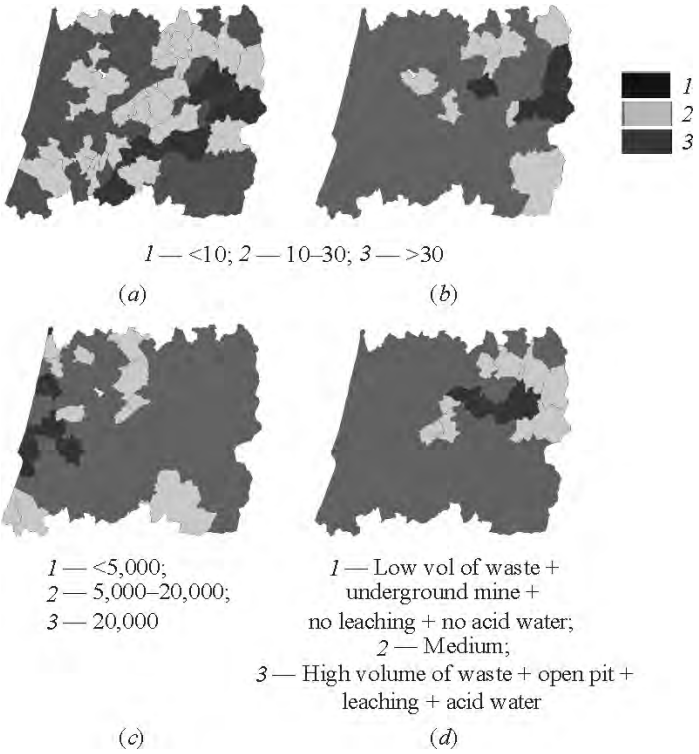

Figure 3. Classification of the vulnerability indicators in maps of the Central region: (*a*) water system per municipality; (*b*) number of mineral occurrences per municipality; (*c*) number of inhabitants per water system per municipality; and (*d*) volume of waste + type of mine + acid water.

3.3. VULNERABILITY

In the first methodology approach, all indicators were classified in the same weight and for vulnerability the water supply was used in the

form of indicators such as “inhabitants per water system” and “number of systems per municipality”. The indicators used in the second methodology approach for vulnerability were based in damage potential indicators (economic stakes, income, property, etc. at risk) and coping capacity (funds available for mitigation, insurance, etc.), which are opposite concepts in risk assessment (Figure 4). The damage potential indicators were regional GDP per capita and population density. The population density respects the damage to humans, if it is high, the risk of more people be affected by the hazard is higher. The choice of the three classes was based not in EU reference, for instance, but in the characteristics of the region (Schmidt-Thomé, 2005).

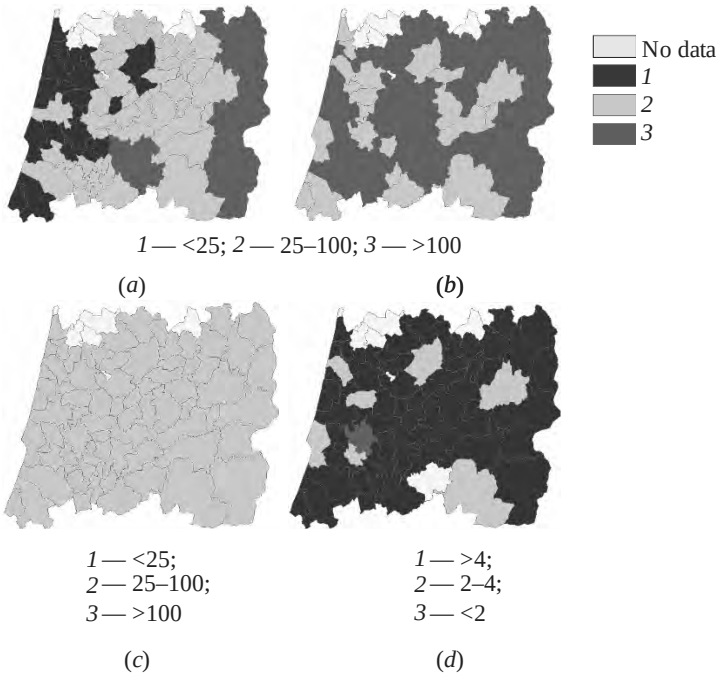

Figure 4. Vulnerability indicators: damage potential (*a* and *b*) and coping capacity (*c* and *d*): (*a*) population density per municipality; (*b*) regional GDP per municipality; (*c*) national GDP per capacity; and (*d*) number of doctors per 1,000 inhabitants.

The coping capacity indicators were national GDP per capita and number of doctors per 1,000 inhabitants. National GDP means that poor regions benefit from the richer regions GDP and if the number of

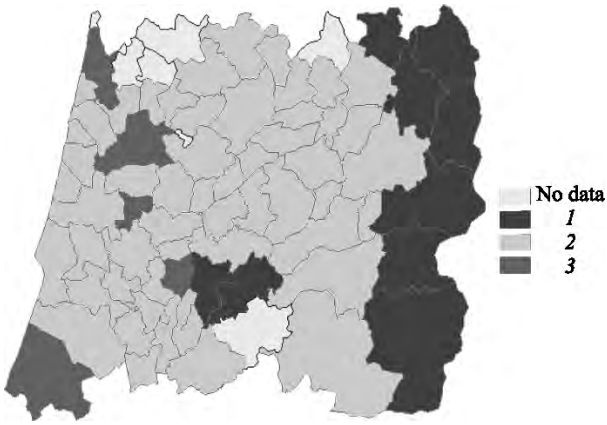

Figure 5. Synthesis vulnerability map composed of Population density + GDP per capita + Doctors per 1,000 inhabitants + National GDP per capita. 1 – lower vulnerability; 2 – medium vulnerability; 3 – higher vulnerability.

Figure 6. Synthesis risk map composed of hazard potential map and vulnerability map. 1 – lower risk; 2 – medium risk; 3 – higher risk.

doctors per 1,000 inhabitants is high, the response to a disaster is more efficient and the risk is lower than when the number of doctors per 1,000 inhabitants is low and the response to a disaster is less efficient (Schmidt-Thomé, 2005), the same principle is applied to the number

of firemen per region. Although, in this study, firemen per region is not available.

The classification of doctors per 1,000 inhabitants was made considering the biggest quantity of doctors per 1,000 inhabitants the lower risk in that case the synthesis map of vulnerability consists of the sum of all the indicators used to characterize damage potential and coping capacity (Figure 5). The combination of hazard potential and vulnerability resulted in the risk map that represents the methodology applied (Figure 6).

4. Discussions

The selection of the indicators to use in the first approach, in this specific risk assessment, was based in the criteria that knowledge of this mineralisations and mining activity would help to identify the fragilities caused in the region. In fact, some mineralisations where the U is present in a stable form, the mobility and risk of uptake by the plants or to pass into the solution and be transported in superficial waters is lower in other cases is high.

The indicator "distance from the uranium mines and mineral occurrences to the land use categories" (see Figure 1a) was used because only in certain uses of the soil there is an actual risk of introduction of U into the food chain, that is, for instance, agricultural soils used to grow crops. Even so, it depends on the vegetables that are cultivated (Bettencourt *et al.*, 1988). Interior waters used for irrigation of agricultural soils constitute a risk for uptake by plants or the water be ingested by animals. At smaller distance from the mines or mineralisations, and if the U is present in mobile forms, such as, in secondary minerals (Lencastre, 1965; Pilar, 1969), the risk of contamination increases in these two categories of land use.

The relevance of the lithology indicator (see Figure 1c) stems from the knowledge that closely concentrated uranium mineral occurrences is mainly due to the granitic rocks and their bordering shales (Cavaca, 1968). Many studies show that natural gamma ray exposure (see Figure 1d) is much more important to humans exposure than man-induced radioactivity (Plant *et al.*, 2003; Ghiassi-Nejad *et al.*, 2001) and that was the reason to choose natural gamma ray in this study. In the region, some authors does the connection of natural gamma ray

and risk to human exposure in house environment (Neves *et al*., 2003). It is possible to observe that the granitic intrusions showed by the lithology coincide with the natural gamma ray areas and mines and mineralisations. In fact, these three indicators, as well as the U concentrations in stream sediments, represented by the geoaccumulation index (see Figure 1b), are the most important to characterize this hazard in this first approach.

The indicator "water systems per municipality" and the indicator "inhabitants per water system" were considered relevant (see Figure 1e, f): The first, because small systems for small villages are more vulnerable to contamination related to older uranium mining activities because treatment and control does not include sufficient parameters in these small systems. More systems per municipality mean smaller systems per municipalities. The second was considered important due to the fact that water for human consumption is at the highest risk for radioactivity contamination. This information was obtained only for the groups of systems per municipality. However, in future, it should be developed with more detailed information.

In the second approach methodology although vulnerability is better introduced in the study, the less detailed information may not be sufficient at the scale of work. The importance of its application was to show the use of a balanced number of hazard potential and vulnerability indicators and the use of socio-economical indicators such as population density and national and regional GDP per capita (Schmidt-Thomé, 2005). In the case of regional GDP per capita because reflects directly the economical risk, if a region have higher GDP per capita means that in case of a desaster the region the damage is higher than in a poor region with low GDP (Schmidt-Thomé, 2005).

The first approach methodology is more accurate because represents a continuous image, the problem is the lack of data to represent all the important indicators at this scale. This first approach puts in evidence that not always areas classified with the more vulnerable mines coincide with areas with high risk of naturally enriched areas (see Figure 2). Either way, both methodologies show the same region with higher risk.

The interior regions show to be more vulnerable because systems are smaller located in small aquifers and in some cases can be influenced by mining drainage. Near sea coastal areas, the water systems are bigger, meaning that they supply much bigger number of inhabitants

and much less number of systems. These are usually superficial waters that are submitted to high quality control. Moreover, these bigger systems are located outside the uranium province which reduces the risk considerably. Thus, the bigger systems in coastal areas have less risk of uranium contamination.

5. Concluding Remarks

Both methods present a similar risk area, the uranium province, althoughugh the first approach has different and continuous data. In the first approach, the region with higher risk show the classification of the more vulnerable mines (open pits, with acid mine drainage and more volume of waste material especially with poor ore and the remains of the mining treatment plant) and bigger areas only related with natural enrichments in uranium.

Economic and social vulnerability maps show coastal municipalities with higher vulnerability. Interior municipalities have more uranium mines and less doctors per 1,000 inhabitants this way are more vulnerable to this specific hazard.

Higher risk municipalities have more open pit uranium mines with acid mine drainage, high volumes of waste materials and medium population density, GDP per capita and less doctors per 1,000 inhabitants. These municipalities are Gouveia, Guarda, Mangualde.

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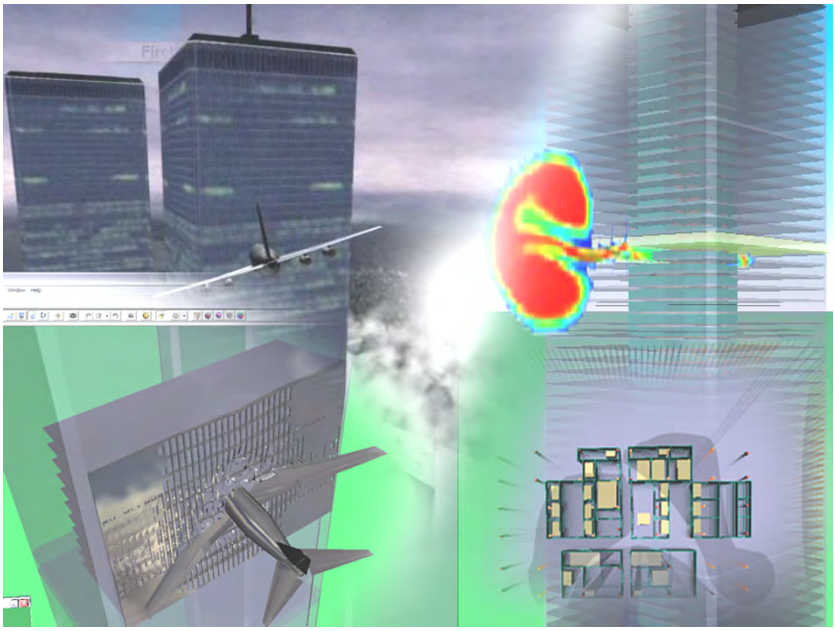
THEME 2

FIRE AND COLLAPSE RISKS OF URBAN STRUCTURES



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QUESTIONS ON THE WTC INVESTIGATION

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Abstract: A critique of the World Trade Center investigation with respect to the cause of the collapse of towers 1 and 2 is presented. The official investigation conducted by the National Institute of Standards and Technology (NIST) concluded that the collapse was due to the fires heating the core columns that were stripped of insulation by the aircraft impacts. An alternative cause is considered that puts the cause on insufficient insulation of the steel truss floor members. Evidence for the latter is supported by NIST analysis of a truss member, Underwriter Laboratory furnace tests of the floor assembly, and engineering calculations and scale model tests conducted at the University of Maryland. The presentation is couched in terms of 10 questions for NIST.

Keywords: collapse cause; fire; investigation; WTC

1. Introduction

Many questions could be asked of the NIST World Trade Center investigation. The investigation was convened nearly a year after the event when Congress passed a special act to give NIST authority to investigate catastrophes related to the built environment, and funded it with $16 million. They investigated many aspects of the event related to the fire and collapse of the twin towers including the egress of people, the fire service response, the detection system, and of course

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the fire and structural collapse. NIST actually began an investigation activity shortly after 9/11 with an inquiry into the fire behavior through the acquisition of photographs and video from the news media. I assisted in this acquisition as I had begun to speak out on things that bothered me about the investigation, or lack thereof. As I spoke out, I came in contact with two women, Sally Regenhard and Monica Gabrielle, who were members of the "9/11 families," losing a son and husband, respectively. They were determined to have an investigation on the collapse of the buildings, and formed the Skyscraper Safety Campaign, a nonprofit organization. Their 'in-your-face" actions got the attention of Congress, who listened, and launched the NIST investigation. At the time, I told them NIST was the best organization to do the job. Little did I realize that the NIST heart was not in it, and its efforts would not be proactive, but reclusive. While NIST had public hearings during the course of discharging their findings, they were limited to 5-min presentations by the public, and no response to submitted questions or comments. There was no transparency of their effort, and even their Advisory Board did not know when they would finally release conclusions until October of 2004. The conclusion was formally contained in a report consisting of a 10,000-page document that defies reading and analysis. Although Sally and Monica were updated in bi-weekly conference calls mandated by Congress from NIST, they very early became discouraged and concerned with the NIST progress and style. I participated in all of the NIST hearings, and the related Congressional hearings, and in that way followed the NIST progress. In October of 2004 their conclusions on the cause of the building collapse was a surprise to me. While I can find issues with their investigation of the event in assembling information through the lack of calling witnesses, issuing subpoenas, and applying normal proactive legal processes, I will primarily focus on the issues related to the fire and the collapse of WTC 1 & 2.

Specifically I will demonstrate why I believe the NIST conclusion is deficient and I will offer an alternative conclusion. The significance of these two conclusions is significant, as it bears on the responsibility for the collapse of the towers. The NIST conclusion essentially puts the primary cause on the impact of the aircraft, while the alternative conclusion lays it at the feet of fire safety design. The correct answer bears on the practice of fire safety.

Let us recall the events of 911 (Figure 1–3). WTC 1, the North tower, was struck first at about the 96th floor. The South tower, WTC 2, was struck about 20 min later at about the 81st floor. We would then see the South tower fall first in 56 min, followed by the North in nearly twice the time, 102 min. WTC 7, not struck by any aircraft, fell after 7 h of unchallenged fires. A curious aspect of the failure times for WTC 1 and 2 is that the insulation of the steel floor truss system had about twice the thickness in WTC 1 than 2. This coincidence will be the basis of the "alternative hypothesis" for the collapse.

Figure 1. Impact of WTC 1, North tower.

Figure 2. Impact of WTC 2.

Figure 3. Collapse of the South tower.

1.1. MY INVOLVEMENT

I became involved in the WTC investigations as an observer and a fire scientist. I followed the NIST activities throughout. In late September I was invited to be part of the American Society of Civil Engineering team of experts that were to attempt to investigate the scene. I was asked to be on a backup team and began to receive emails on activities of the ASCE team at the WTC site. The ASCE did not get easy access, and were initially concerned about the pending and later actual sale of the steel debris from the scene. This is where I began to speak out as the loss of the primary steel elements that were coded according to location could provide vital information about the temperatures achieved. Metallurgical analysis could yield the temperatures and help to pinpoint the role of the fire in the structural collapse. Needless to say, most all the steel was sold off, and only little remained as a result of voluntary efforts of the Civil Engineers of New York (CEONY). Subsequently, I never became part of the ASCE team.

My involvement during the course of the investigation is summarized below. I was not a paid consultant, nor did I have any research contracts to support my work:

September 2001: presented seminar to NIST for conducting a scale model simulation of the impact and fire

Nov 2001: spoke out against sale of steel in news media, NY officials

Dec 2001: affiliated with the Skyscraper Safety Campaign (SSC)

Feb 2002: assisted NIST in accessing NY Times photo archives

Attended all NIST public hearings, submitted extensive comments and questions

Attended all Congressional Hearings on WTC

Published and presented papers on WTC in peer-reviewed venues 2002–2007 (Quintiere *et al*., 2002; Quintiere, 2004; Wang *et al*., 2007)

Conducted tests on insulation in cooperation with Isolatek

Co-led student project to simulate floor fire of WTC 1

Investigated fuel load on Marsh & McLennan floors of WTC 1.

1.2. WHY QUESTIONS?

The NIST investigation was done in virtual secrecy with periodic hearings to give progress. It was not until October in 2004 did NIST present a conclusion. Up until that time, it was not clear what they would conclude. NIST has not responded to written questions, but has accepted comments and posted some on their website. A dialogue has not been conducted between the public, press and NIST. In addition, litigation related to the civil suit between the WTC lease holder and the insurance companies never would be made public. Conspiracy theorists have dominated the web pages and received strong recognition in the media. Yet responsible criticism has been minimal. A quietly written book by Arthur Scheuermann (2007), a NYC retired fire chief with a knowledge of building structure, presents an balanced quailtative analysis of the WTC collapse. This book should be referred to for an objective report of the background on the WTC construction and the events of 9/11. Other excellent books on the history of the WTC and on the accounts of those trapped in the twin towers on 9/11 have been written by NY Times correspondents: Glanz and Lipton (2003), and Dwyer and Flynn (2005), respectively.

What is lacking from NIST is a clear account of the logic they used in explaining the collapse mechanisms. It is one thing to state the cause and imply their computation by computer codes; it is another to clearly illustrate the physics behind the collapse mechanisms. Perhaps that is the reason for so many conspiracy theories. A contrast can be made to the investigation of the Columbia shuttle accident that occurred after 9/11 and whose investigation concluded before the NIST final report. The NASA team clearly identified the cause by using the photographic evidence, analysis and clear testing done at Southwest Research Institute. No conspiracy theories here.

Let us examine the evidence and let me try to lay out the basis of alternative to the NIST conclusions. In doing so, I will try to explain the logic in the simplest way possible, yet try to keep true to the physics of the problem.

1.3. THE NIST CONCLUSIONS

The NIST work is a tome to read. It is made up of several lengthy progress reports that then were melded into a final report of approximately

10,000 pages. Each investigator wrote their separate analyses; as I learned there was not a full integration of the work as each passed their work on to the other. A spiritual leader of the investigation never emerged. Because of the lengthy reports it is difficult for me to explicitly document all of my NIST sources, but I will do the best I can. I list the reports that I used:

December 2003, Public Update on the Federal Building and Fire Safety Investigation of the world Trade Center Disaster, NIST Spec. Pub. 1000-4, NIST, DoC (NIST 2003).

Reports of the Federal Building and Fire Safety Investigation of the world Trade Center Disaster, Drafts for Public comment, NIST, DoC, June 23, 2005 (NIST 2005a).

Final Report of the Federal Building and Fire Safety Investigation of the world Trade Center Disaster, Drafts for Public comment, NIST, DoC, September 2005 (NIST 2005b).

The NIST findings state (pp. xliii–xlviii) (NIST 2005b):

> "In WTC 1, the fires weakened the core columns and caused the floors on the south side of the building to sag. …The time from the aircraft impact to collapse was largely determined by how long it took for the fires to weaken the building core and reach the south side of the building and weaken the perimeter columns and floors."

In WTC 2, the collapse is based on similar reasoning but the core was more severely damaged in the southeast corner.

> "The WTC towers likely would not have collapsed under the combined effects of the aircraft damage and the extensive, multifloor fires if the thermal insulation had not been widely dislodged or had been only minimally dislodged by the aircraft impact..." "On September 11, 2001, the minimum specified thickness of the insulation [0.5 inches] was adequate to delay heating of the trusses…"

In other sections of the reporting, NIST concluded that the core columns, heated from lack of insulation, "softened and shortened" which led to pulling in the exterior columns and then collapse. The lack of insulation on the core columns removed by the aircraft impact

is their main basis of the root cause of the collapse. The originally specified insulation thickness on the truss floor system of 0.5 in. was declared sufficient for the fire conditions, and therefore not the root cause of the collapse.

1.4. OTHER COLLAPSE SCENARIOS

Other collapse scenarios have been suggested in the literature. This is how I interpret them.

The Weidlinger investigators (Abboud *et al.*, 2003; Beyler *et al.*, 2003) were part of the civil case brought by the leaseholder against the insurance companies, but did publish some of their work. They did the work mainly in 2002 and concluded all of the insulation in the path of the aircraft was stripped off. Their work is shown in Figure 4. But they admit that the structural collapse calculation have issues of accuracy as in their computations, the south tower WTC 2 collapses on immediate impact of the aircraft. As that did not happen they needed to make adjustments. The core columns are completely stripped of insulation in their work.

Other collapse scenarios are based on the floor truss systems as the cause. These are based on the trusses being heated between 400–600ºC and failing. They are done with structural models at these temperatures, and do not consider the needed fire conditions that would cause these temperatures. Usmani *et al.* (2003) show that the heating of the trusses would cause the instability of the external columns due to sagging of the trusses. Burgess and his team (Choi *et al.*, 2003) indicate that the trusses can fail at their connections. Indeed, the NIST group arrives at a similar conclusion, but apparently does not believe the fire can achieve the needed temperatures (p. 96 in NIST, 2005b). Figure 5 shows the NIST result.

They find the following consequences if the truss achieved these temperatures:

340ºC diagonals buckle

400ºC knuckles fail

510ºC Interior seat bolt shears

650ºC Truss walks off seat.

If trusses are heated to 500–600ºC, the floor can fail.

There are two likely collapse scenarios:

Core columns fail as stripped of insulation and heated by fire: as contended by NIST in their findings, or

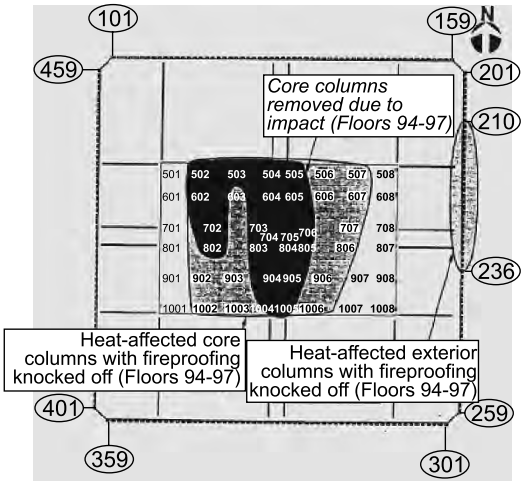

Figure 4. Damage computed by the Widlinger group. (Abboud *et al.*, 2003.)

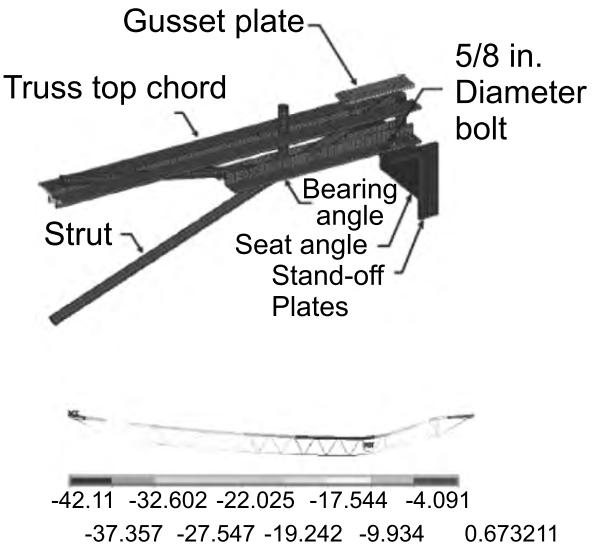

Figure 5. NIST truss computations.

Trusses fail as heated by fire (with insulation intact) as due to the instability of the external columns according to Usmani *et al.* (2003), or the trusses fail at the connections according to Choi *et al.* (2003) and the NIST truss computations (2005b).

It will be shown that the second conclusion can be supported by calculations, scale model tests, and the standard furnace test results of the truss floor assemblies conducted by NIST. The stripping of the core column insulation is critical to the NIST conclusion, and without it they cannot get the buildings to collapse. Although NIST did not mention this stripping until they presented their conclusions in October 19, 2004, I first heard it in early 2003 at a local ASME Washington meeting as presented by NIST scientist, T. McAllister. No scientific justification was given for the stripping except that it was in the path of the aircraft. I thought at the time it was influenced by the Weid-linger results (Abboud *et al.*, 2003). Indeed, Kevin McGrattan, in a recorded conference presentation to the Nuclear Regulatory Commission on September 11, 2001 states: "that [insulation removal] will become a pivotal part in the explanation of why these buildings fell down." "It will carry on through the rest of all the modeling." He attributes it to the work of Terri McAllister. The NIST area on insulation removal is depicted in Figure 6.

The damage computed by various investigators has differed widely, and in a recent analysis, a group at Purdue (Irfanoglu and Hoffmann, 2008) states that, "...Objective evaluations of the simulation results indicated that identification of the number and distribution of columns damaged immediately by the impact was quite sensitive to the input parameters." In a press release last June 2007, the Purdue group stated that their results confirm NIST. They go on to say that, "It is evident from observation and our simulations that the debris of the aircraft went through the WTC structure at stories 94 through 97. Much of the fire insulation would have been scoured off leaving the steel elements unprotected during the immediately following fire event."

But there is no analysis or data to support the effect of aircraft debris with the removal of the insulation. They conclude that, "For both the intact and plausible compromised core states considered, it is estimated that a core collapse mechanism could have been initiated in WTC-1 if the tower core column temperatures were elevated to approximately 700ºC." How results of the damage calculations lead to the removal of

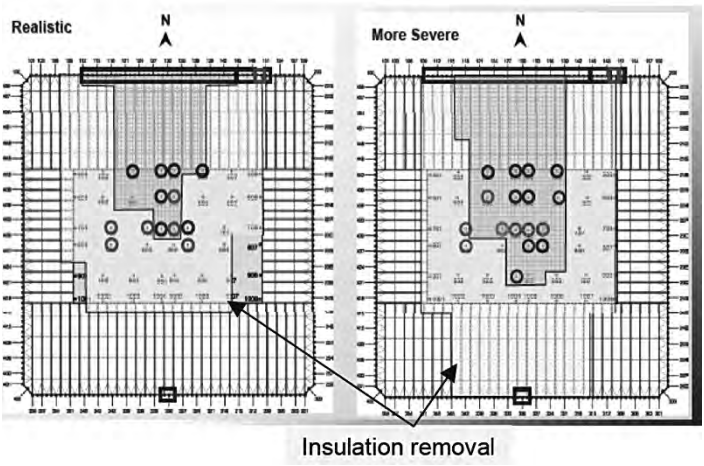

Figure 6. Illustration of the NIST impact damage and the area of insulation removal.

insulation is a key point in collapse scenario 1, mentioned above, and needs more justification in my opinion.

2. Ten Questions for NIST

I will pose ten key questions to NIST on their findings, and by doing so will elaborate, and indicate the basis for the second hypothesis: insufficient insulation on the trusses.

2.1. QUESTION 1: WHY AND HOW WAS INSULATION STRIPPED?

In the NIST modeling, it was *assumed* that the insulation was stripped if debris is sufficient to break gypsum board. NIST did conduct experiments to determine the adhesive strength of the insulation to the steel, but never related those results to any analysis. They also conducted what appears to have been an ad hoc experiment in which 0.3-in. diameter pellets at 350 mph stripped the insulation on 1-in. diameter steel bars. (NIST, 2005b, p. 117). No discussion of the rationale of this experiment is given. If the removal of the insulation is such a necessary condition for the core steel to be heated, then more evidence to support this assumption is needed.

2.2. QUESTION 2: WHY WAS THE DEBRIS STEEL SOLD? COULD IT HAVE PROVED NIST CORRECT?

All of the primary structural steel was coded, and the steel from the fire floors could have been segregated for analysis. If NIST had the steel they claim got hot and shortened, it could prove their case.

This is an excerpt of a letter I wrote, when I became an advocate for the investigation. The letter was never answered, along with many telephone calls pleading for the preservation of the steel.

> November 27, 2001
>
> Michael Burton, P. E.
> Executive Deputy Commissioner of DDC
>
> 30-30 Thomson Avenue
>
> Long Island City, NY 11101
>
> …The **steel members are coded** and they could be segmented by floor so that analysis could indicate the basis of failure… When we live in times that an aircraft that crashed in the sea can be put back together, it is not beyond expectations that similar action can be taken here…

The steel that was saved is due to the voluntary efforts of the Civil Engineers of New York (CEONY) who went to the dumpsite. It was not done in the best systematic way and much of the critical pieces from the fire floors were not saved. NIST did not acquire the steel until mid-2002, and only received about 1% of the core steel of the fire floors. "None of the recovered [core] steel samples showed evidence of exposure to temperatures above 600 ºC for as long as 15 min. This was based on NIST annealing studies that established the set of time and temperature conditions necessary to alter the steel microstructure. These results provide some confirmation of the thermal modeling of the structures, since none of the samples were from zones where such heating was predicted" (NIST, 2005b, p. 176). It would have proven far better if steel were found that confirmed the needed temperatures. These annealing studies of the steel were done by NIST

late in their investigation, as they appeared to not initially realize the benefit of metallurgical studies of steel grain size analysis to assess attained temperature. Moreover, they do not fault the removal of the steel as an error by the investigators on the scene.

The steel could have served as a thermometer that indicated the maximum temperature achieved in a given location. Having that mapping of the fire conditions could have proved invaluable. Losing it is spoliation of a the fire scene.

2.3. QUESTION 3: DID NIST USE THE CORRECT FUEL LOAD?

I believe the fuel loading used by NIST is in error and was too low. This, I believe, led to short fires that were insufficient to heat the steel to failure unless the insulation of the core was missing. Note that most of the floor truss insulation was consider intact by NIST except for the immediate impact areas. These short fires could not heat the insulated trusses to failure in the NIST fire computation, in my opinion.

NIST used 4 lb/ft^2 (19.5 kg/m^2) in their analysis of WTC 1, and presumably did the same for WTC 2. Typical office fuel loads range from 24 to 100 kg/m^2 (wood equivalent) and average roughly 60 kg/m^2 (Chow *et al.*, 2006). The NIST value is low over this range. Based on an analysis of the same floors audited by NIST, we obtained a different value for the fuel load of the Marsh & McLennan 96th floor (Stewart, 2005). For the same fuel items that NIST used, we obtained about 135,000 lb, giving us an estimate of the NIST load of 4.3 psf. This agrees with the NIST computed load of 4.0 psf, and gives a check on our accounting methodology for the same furniture. When we included the additional storage items and the 50% load in the common files that NIST had omitted, we reached about 300,000 lb. or 9.7 psf (44 kg/m^2). We think this difference in fuel load needs an explanation from NIST.

By the way, access to the furniture information was obtained through the connections of the Skyscraper Safety Campaign by reaching out to the 9/11 families. A family member from the supplier of the furniture gave me access to the AutoCAD drawings of the furnishings. Kate Stewart discovered and accounted for the central file cabinets ignored by NIST (170 4-drawer), and also made estimates for the movable load

brought in by the occupants. In talking to people who had access to the Marsh & McLennan floors, I was told that they were “paper hogs” and had piles of paper on the windowsills. The architectural drawings of the furniture layout on the Marsh & McLennan floors clearly show a ring of central file cabinets. For NIST to have missed the files is a gross error.

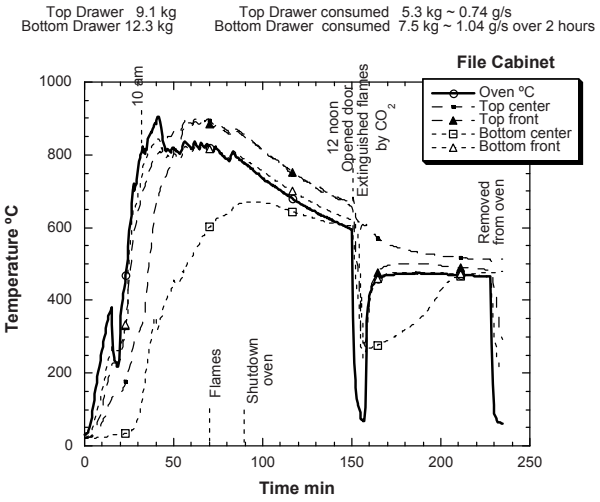

Figure 7. Burning of paper in file drawers of a metal cabinet.

After communicating our results to NIST, some scientists from NIST remarked to me that paper in file cabinets does not fully burn. Not finding any information on this subject in the literature, I conducted my own experiments. Two file drawers in a cabinet loaded at 50% and to full capacity were subjected to furnace conditions of 600–800ºC for 2 h. Figure 7 shows the results of the tests.

Approximately 60% of the paper was vaporized with the remainder consisting of char and ash. This is not an uncommon distribution for cellulosic material in a fire. Hence, the file paper would follow the behavior of wood in a fire.

Using a low fuel load would reduce the heating time of the fire, and that is the primary factor in the heating of the structure. Figure 8 illustrates the typical floor conditions as depicted by NIST (NIST, 2005b). The trading-floor was indicative of WTC 2. NIST modeled its fires by reconstructing facsimiles to the Marsh office workstations.

Figure 8. Actual WTC occupancies according to NIST.

We think, our conservatively low estimate of 44 kg/m^2 compared to 19.5 used by NIST needs to be addressed.

2.4. QUESTION 4: IS THE NIST FIRE MODEL ACCURATE?

The NIST computed fires only last about 20 min (Figure 9) in any give location on a floor, but the flames move about the floor. NIST validated their model by comparing with the photographic evidence of the window flames. As the smoke in these fires at the windows have a visibility of about 1 m, it is not possible to observe the nature of the flames within the building. The NIST validation strategy may be lacking as they cannot see the internal fires.

There are several factors that influence the accuracy of the NIST fire model. It is a large eddy based fluid flow model. There is no direct accounting for the local scale of turbulence or the small-scale combustion phenomenon. Some factors contributing to its uncertainty are listed here:

Grid size for computations = 0.4 m

Scale of combustion ~1 mm

No validation for predicting temperatures in a fire plume

Model has never validated for a large fire in a compartment

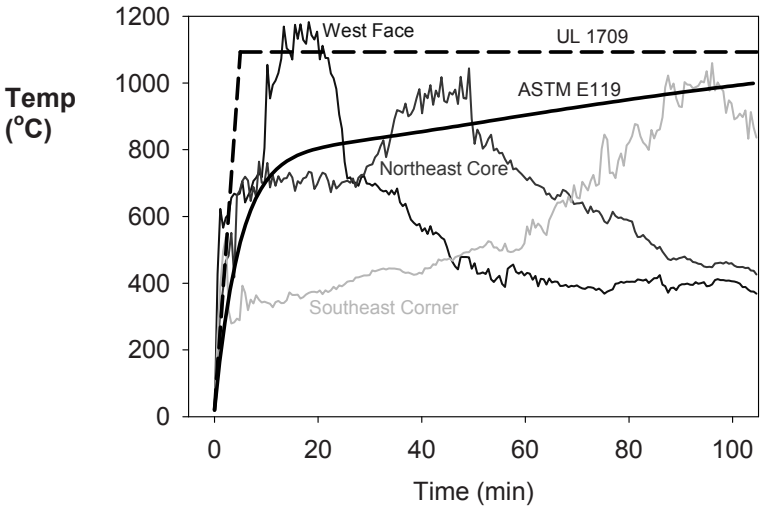

Figure 9. Average temperatures predicted for WTC 1, 97th floor. (From McGrattan, 2005).

Large fire measurements suggest higher flame temperatures than predicted >1,300ºC.

Both the fire and the structural models used in the prediction of the WTC have never been used for such computations. NIST admits they have stretched their application. In view of such uncertainty, it is disappointing that alternative approaches were not invoked.

Alternative computations are available and have been based on experimental data. Formulas have existed for decades and have served as the basis for design estimates. Recently the SFPE has produced a guide on such formulas. Figure 10 shows results for temperature and its duration based a formula established by the extensive CIB data base (Quintiere, 2004). Here is an example of applying the CIB correlations to the WTC fires with a fuel loading of 7.5 psf (34 kg/m^2). It is compared to NIST temperature for 4 psf loading at a given floor location. The results also show the standard fire temperature furnace curve and the temperature suggested by Beyler *et al.* (2003). The CIB fire is longer than the NIST local fire prediction, and indicates fire heating beyond the collapse times of each building. These CIB-estimated results will be used later to compute the steel temperature in the trusses.

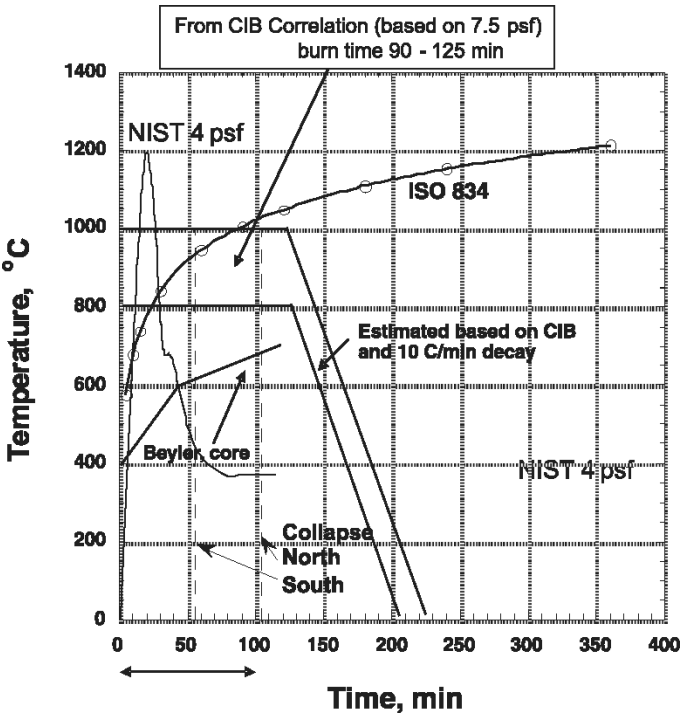

Figure 10. Estimates of the fire temperature.

2.5. QUESTION 5: NIST SAYS THE ORIGINALLY SPECIFIED INSULATION THICKNESS WAS ADEQUATE. IS THIS CORRECT?

There is a long history concerning the insulation of the trusses in the WTC towers (Glanz and Lipton, 2003). NIST concludes that the insulation as used in both buildings would have been adequate to keep the buildings from falling had there been no loss of insulation in the core. The history of this insulation thickness from its design in 1965 of 1/2 in. to an upgrade initiation in 1994 of 1–1/2 in. is a story that fire protection engineers need to understand. The process of the insulation design is fraught with nontransparency and needs clarification.

Table 1 shows the insulation thicknesses and its history. It is striking the NIST did not have full data on all of the elements. But the most striking is the change made to the trusses. These changes are a

TABLE 1. Insulation thicknesses (Taken from NIST, 2005b, p. 70)

Component	Specified	Installed	Used in Calculations
Truss			
WTC 2: Original	1/2	3/4	0.6
WTC 1: Upgrade	1.5	2.5+/–0.6	2.2
Core Columns			
WF Light	2 3/16	?	2.2
WF Heavy	1 3/16	?	1.2
Box Light	?	?	2.2
Box Heavy	?	?	1.2

portrayal of the insulation design process. NIST's lack of probing in this area through subpoenas and testimony is remiss. The basis for the original design, and the change in 1994 should be a lesson learned. The stated "installed" insulation thickness of the WTC 1 upgrade should be questioned, as its source is a NYNJ Port Authority audit report with no photographic evidence. It should be realized that the installer was requested to upgrade the thickness on the Marsh floors of WTC 1 from 1/2 (or measured as 3/4 in.) to 1.5, but instead put on 2.5 in. on average. On a 1-in. diameter steel truss rod, that would make the overall diameter 6 in., instead of 4. This is an unlikely application of insulation in my opinion, and is subject to question.

My information on the history of the truss insulation is summarized below. I am making estimates on the basis for the original specification and changes.

Basis of original specification:

1966 memo (Tishman, J. R. Enders: cost analysis)
Cafco D for ULI-86-3: 8 × 3/4 in. beam-floor assembly 1/2 in.
Insulation ~ 4 h.
1969 memo R. Linn to DiBono "beam cover should be 1/2 in."

Basis of 1994 change: (Upgrade on re-evaluation)

UL G805: 1 1/2 in. ~ 2 h
(but UL N826 without deck insulation: 2 1/16 in.)

2001 Burro-Happold report to NYNJPA: “insulation adequate”, recommends 1.3 in.

Floor assembly never tested until done by NIST in 2003 at UL:
Rating ranges from 3/4 h for 1/2 in. to 1–2 h for 3/4 in.
Tested at 17 and 35 ft spans, not longest 65 ft.
Rating based on collapse criterion, not on temperature achieved.

The ratings for the UL furnace tests were based on loaded assemblies, and therefore the failure time is based on structural collapse. Note the long span truss of 65 ft could not be tested. Normally the test assembly is not loaded and temperature is the criterion for the rating; in some areas of the world only the temperature criterion applies. By examining the temperatures achieved and by assuming the standard time-temperature curve represents a reasonable fire (Figure 11), some conclusions on failure can be drawn. Especially since structural models indicate failure of the floors trusses at temperature of 400–600ºC. The UL tests of 17- (scaled) and 35-ft truss spans give temperatures indicative of failure, and consistent with the temperatures need to cause structural failure of the floors in times of 58–86 min. Note the following:

Time to reach 593ºC (average)—66–86 min.

Time to reach 704ºC (max.)—58–76 min.

NIST computed truss “walks off seat at 650 ºC.

The variation in the UL times is due to three separate tests at 3/4 in. of insulation and one at 1/2 in., indicative of WTC 2. One might question why there is a 28-min variation in the results for simple thermocouple measurements in a standard time-temperature furnace test. But that is a question for the accuracy of the test, not these general results. For these, times of 58–86 min are consistent with the failure time of 56 min for Tower 2. So the UL tests do support that fire conditions can fail the trusses in WTC 2.

WTC 2, 19 (mm) (3/4-in. insulation): failure times are 70 and 110 min for WTC 2 and 1, respectively, for no loss of insulation. A small loss in insulation reduces these times sharply, especially after 20% is lost. This result suggests that the loss of insulation on the trusses was not likely, as collapse would have resulted much earlier than in reality.

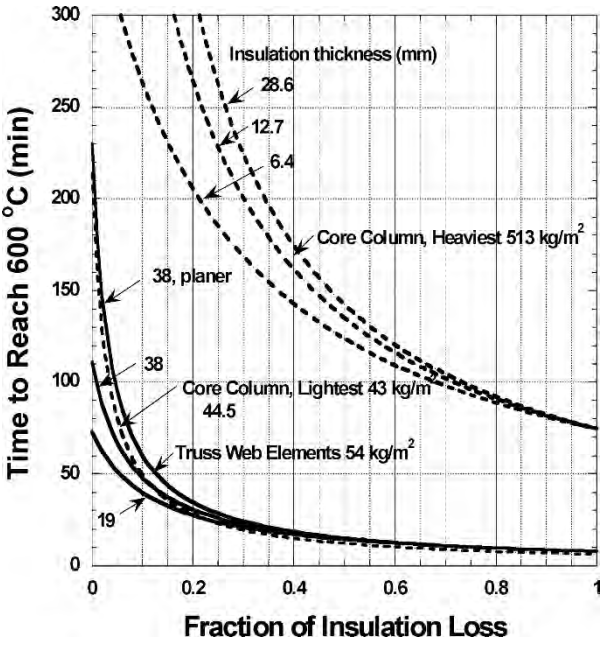

Figure 11. Steel time to reach 600ºC failure criterion.

However, the loss of all insulation on the heavy core columns results in a failure time of about 75 min; this is not so inconsistent with the actual failure times of 56 and 102 min. But the correspondence to the truss computed times are a much better match. Moreover, more than 50% of the insulation must be lost from the core heavy columns to yield failure times consistent with the event. These computations support the trusses as the root cause of the collapse.

2.6. QUESTION 6: ARE COMPUTER MODELS SOLELY SUFFICIENT?

NIST admits to stretching the envelope on computer models, never used before on such a complex fire. Damage predictions vary extensively. The models cannot fully resolve turbulent combustion, and small details of construction as represented by the insulation and

connections. So how can NIST accurately compute the fire, and the removal of the insulation by the aircraft?

Alternatives to computer modeling exist. First, computations based on formulas and correlations have been used for analysis and design in engineering. When done, these provide a transparent view of the computational process, as opposed to hidden aspects of computer codes. Second, scale-modeling approaches have been used for design and accident investigation in both fire and structures. This approach not only provides a relatively inexpensive view of the phenomena, but also a measurement workbench upon which to compare computer models. Third, there is always the complete reproduction of the event at its scale. In this case, the reconstruction of a full floor (or quadrant) would have been extremely useful, and within the $16 million budget for this investigation.

2.7. WHY NO FULL-SCALE TEST?

NIST conducted tests involving several workstations representative of the Marsh & McLennan floors. These included some of the steel truss assemblies. But as stated earlier, it believed to be sorely deficient in fuel load. The tests were used to tune the fire model to better represent the workstation fuel load, and are responsible for the 20-min fire durations in any given location. A much more representative reconstruction could have been constructed and tested. As the WTC floor plans were fairly symmetric, a quadrant of one floor could have been a good starting point. A more comprehensive reconstruction of the fuel load should have been assembled, validated and tested. The truss and core temperature could have been measured for various insulation thicknesses. The effect of fire scale on turbulent flame temperature would have been determined from these tests. Then, computer modeling could have been tested.

It was stated an alternative to a full-scale test is physical scale modeling. We conducted such an exercise for the 96th floor of WTC 1 as a senior undergraduate class semester project (Quintiere and Marshall, 2007). The project was funded internally, and cost about $2,000 in materials and equipment.

TABLE 2. Scale rules

Phenomena	Modeling: Scale: $s = l_m/l_p$
Geometry, coordinates	Length ~ s^1
Time	Time ~ $s^{1/2}$
Fire dynamics	Power ~ $s^{5/2}$, Flame height ~ s^1
Fluid mechanics	Re ~ $s^{3/2}$ *(make large enough)*, Velocity ~ $s^{1/2}$
Thermal effects	Temperature ~ s^0, Radiation flux ~ s^0, Convection flux ~ $s^{1/5}$
Structural mechanics (Fracture and buckling)	Stress ~ s^0, Strain ~ s^0

In scale modeling, some compromise must be made in satisfying the key dimensionless groups, but the phenomena of turbulence and combustion function according to their natural scales. Scaling rules are displayed in Table 2 (Wang *et al.*, 2007).

Students considered the office fuel load and the aircraft fuel. Wood cribs simulated a 10-psf (45 kg/m^3) office fuel load. The construction of the structure was based on the heat transfer scaling and required relatively low density material. Measurements included temperature, heat flux, fuel mass loss, and smoke obscuration. Several external columns and insulated trusses (unloaded) were included according to the scaling laws. The insulation on the scale model is based on heat transfer consideration, and is not based on geometric scale. Consequently, the insulation thickness was applied to the complete truss, not the individual components. Photographs of the assembly (model floor with no ceiling) and fire are show in Figure 12 and Figure 13.

Figure 14 shows the results of the scale model in terms of the temperatures. In comparison to the NIST computations for comparable temperatures on the 97th floor, the NIST upper layer temperatures are only about 800ºC for about 20 min, while the model results show a given region is in excess of 800ºC for about 45 min. This is a more severe fire condition. Moreover, the scale model is likely to give lower flame temperatures due the scale effect on radiation. Thus, the scale model shows a similar movement of the fire about the floor as the NIST computations, but more significantly shows a longer duration of the flames.

Figure 12. Scale model floor.

Figure 13. Scale model test in progress.

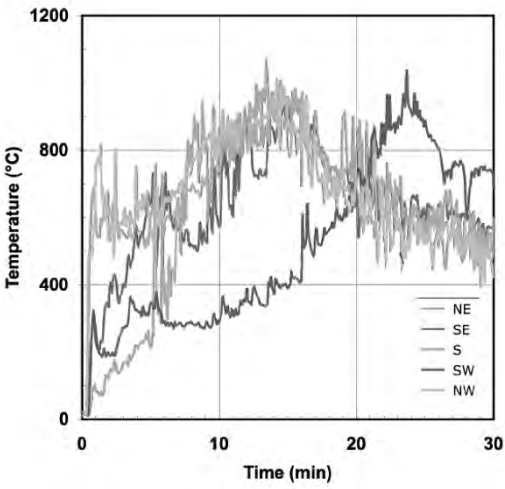

Figure 14. Scale model upper layer gas temperatures for 96th floor, WTC1. Time is in model time, and 89 WTC full-scale time is 20 min model time.

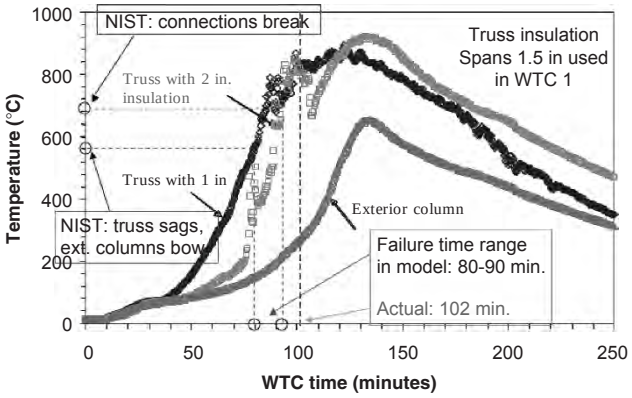

Figure 15. Scale model truss temperatures.

Indeed, the scale model shows in Figure 15 that the steel trusses in the model, with scaled insulation thicknesses of 1 and 2 in., respectively, indicate failure in 80–90 min compared to an actual failure in WTC 1 of 102 min. We feel this gives some credibility of the scale model result, and supports the hypothesis that the trusses are at the root cause.

2.8. QUESTION 8: WHY NO ACCOUNTABILITY?

Perhaps it was not the job of NIST to hold people or practices accountable. But the style of their report should have had the sharpness of focus to indicate where the faults were. Instead, NIST has produced a long list of recommendations, most of which do not tie to the root cause of the disaster. Let me list some of the more notable issues that needed sharpness of focus to bring appropriate accounttability and corrective actions:

Loss of the steel as evidence of temperature

Documentation and analysis of the process for the fire resistance design

Radio communication of the fire service.

NIST had subpoena authority that was not used, and had the ability to hold hearings under oath that was not invoked. This lack of authority should have been a vital part of the investigation.

2.9. QUESTION 9: WHY NOT OFFER SEVERAL HYPOTHESES ON COLLAPSE AS NIST INITIALLY SAID?

From the start of the investigation, NIST continually stated that the end point of the process would be to present hypotheses according to their probability of occurrence (NIST, 2003). NIST original objectives stated:

What is the most probable collapse sequence?

What is the probability of the possible collapse sequences?

Instead, NIST lists one cause without equivocation. What happened to their original plan?

2.10. QUESTION 10: WHAT ABOUT WTC 7?

As we know, WTC 7 collapsed many hours later. It was hit by falling debris from the towers, and that caused damage and fires to occur. NIST has yet to produce a report on the cause of its collapse. Little has been reported. At the NIST NSTAR Advisory Board meeting I attended in December of 2005, discussion centered on whether it was worthwhile for NIST even to pursue WTC 7. As I understand, the report is still a work in progress, 6 years after the event. As the removal of insulation by the impact of the aircraft would not be an issue here, it is imperative to find the cause of the WTC 7 collapse that was solely due to its fires. Some believe diesel oil tanks within the building fed the fires. I contend that these tanks would have played the same role as the aircraft jet fuel that ignited the contents of WTC 1 and 2. This jet fuel burned quickly, and the building contents were the primary source of the fires. The same would apply to WTC 7. Hence, an ordinary building fire, unattended by the fire service, led to a collapse. The design of fire resistance in a building is supposed to prevent the heating of the structure to failure over the expected duration of a fire. This apparently was not the case. Do we have a design flaw?

3. Conclusions

I contend that the NIST analysis used a fuel load that was too low and their fire durations are consequently too short. Only these short fires could then heat the bare core columns as NIST reports. The fires were

too short to heat the insulated trusses to failure. The NIST analysis has flaws, is incomplete, and has led to an unsupported conclusion on the cause of the collapse.

An alternative hypothesis with the insulated trusses at the root cause appears to have more support. Heat transfer analyses, a scale model, and the UL furnace tests all indicate that the steel trusses can attain temperatures corresponding to failure based on structural analyses. This hypothesis puts the blame on the insufficiency of the truss insulation. Something NIST says was not an issue.

The two different hypotheses lead to very different consequences with respect to recommendations and remedial action. I think the evidence is strong enough to take a harder look at the current conclusions. I would recommend that all records of the investigation be archived, that the NIST study be subject to a peer review, and that consideration be given to re-opening this investigation to assure no lost fire safety issues.

Acknowledgements

I would like to acknowledge the following for their support and assistance: Sally Regenhard, Monica Gabrielle and Phillip Wearne of the Skyscraper Safety Campaign, Maryland Fire and Rescue Institute, FAA Technical Center, Isolatek International, University of Maryland Fire Protection Engineering students: J. Panagiotou, K. Stewart, M. Wang, 320 class 2003, faculty: M. di Marzo, P. Chang, A. W. Marshall, and R. Becker (Technion).

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THE PENTAGON BUILDING PERFORMANCE IN THE 9/11 CRASH

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Abstract: Following the 9/11 crash of an airliner at the Pentagon, the American Society of Civil Engineers established a team to study the response of the structure. The team reviewed available information on the structure, the crash loading, and the resulting damage. The team then analyzed the essential features of column response to impact, the residual frame capacity, and the structural response to the fire. Plausible mechanisms for the response of the structure to the crash were determined and recommendations were offered for the future design and construction of all buildings.

Keywords: pentagon building; 9/11; progressive collapse

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H.J. Pasman and I.A. Kirillov (eds.), *Resilience of Cities to Terrorist and other Threats.*

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1. Introduction

On the morning of September 11, 2001, as a part of a terrorist action involving four hijacked aircraft, a commercial airliner was crashed into the Pentagon. Subsequently, the American Society of Civil Engineers established a team to examine the structural performance of the building in this catastrophe. The purpose of the study was to document lessons to be learned for the benefit of the building professions and the public.

The authors constituted the core of the team, which included expertise in structural, fire, and forensic engineering. The team also broadly represented the academic, governmental, and commercial sectors of the profession. The results have been documented in a report (American Society of Civil Engineers, 2003) and are summarized in this paper.

2. The Pentagon

The Pentagon (Figure 1) is one of the largest office buildings in the world, encompassing 6.6 million square feet (613,000 m^2) of floor space. The groundbreaking was coincidentally on September 11, 1941. The Pentagon was constructed by the U.S. Army Corps of Engineers with wartime urgency in a remarkable 16 months. Its name, of course, stems from the distinguishing five regular sides of the footprint.

Although the Pentagon was designed originally as a four-story building, it was constructed with an added fifth story (Figure 2) as the project came in under budget. It is further subdivided into five circumferential rings that are designated A through E from the interior. In the upper three stories, the rings are separated by light wells. The second well from the interior extends to the ground over most of its length and serves as an interior driveway known as AE drive. To conserve steel for World War II, the original structural system, including the roof, was entirely cast-in-place reinforced concrete using normal-weight aggregate dredged from the nearby river.

The floors were constructed as a slab, beam, and girder system supported on columns. This is shown in Figure 3 wherein the horizontal numbered grid lines are in the radial direction of the structure.

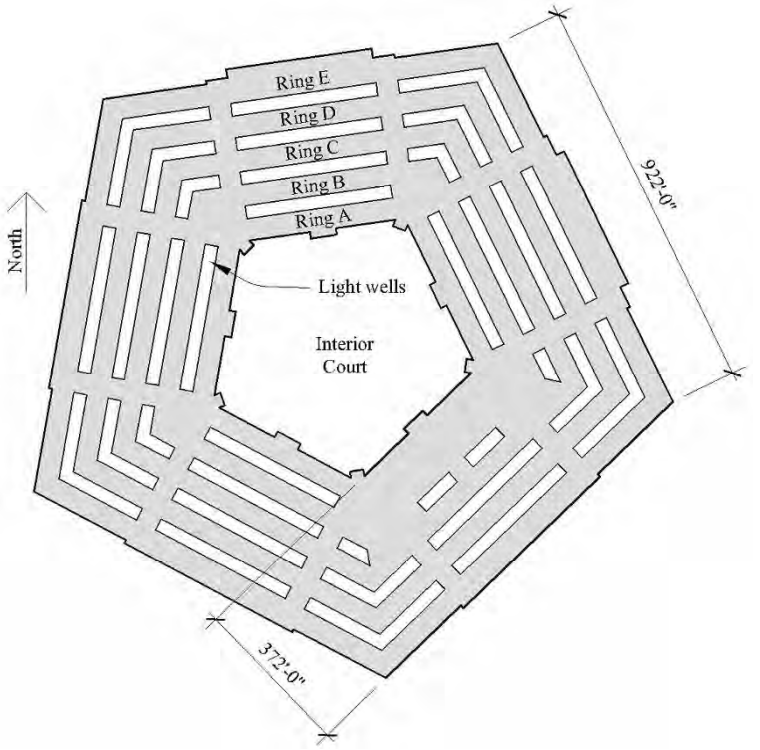

Figure 1. Transverse cross section (to convert feet to meters, multiply by 0.3048).

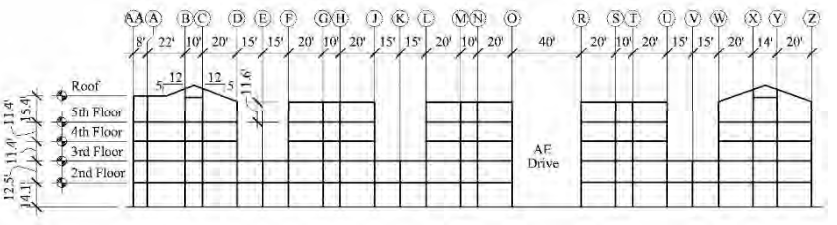

Figure 2. Plan of the Pentagon in the upper stories (to convert feet to meters, multiply by 0.3048).

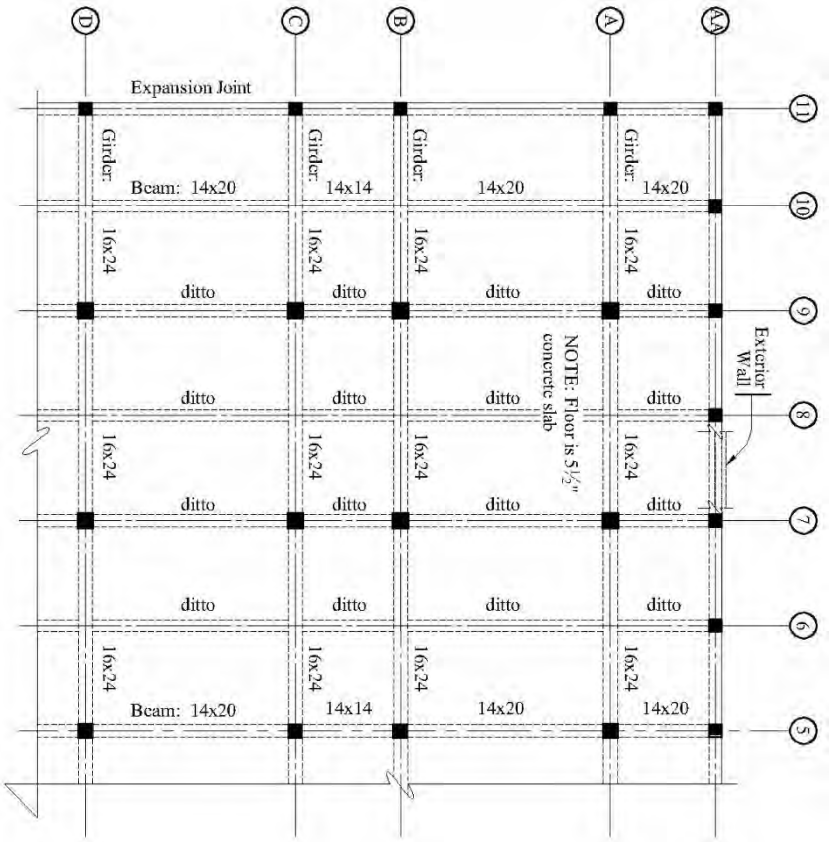

Figure 3. Typical floor framing (to convert inches to meters, multiply by 0.0254).

The design live load was a rather high 150 psf (7.2 kPa), because it was anticipated that the building would be used for records storage following the war. The floor spans are relatively short by modern standards; the 5.5-in. (0.14-m) slabs span to 14- by 20-in. (0.35- by 0.51-m) beams at 10 ft (3 m) on center. The typical beam spans are 10 or 20 ft (3 or 6 m), with some at 15 ft (4.6 m). Girders measuring 16 by 24 in. (0.4 by 0.6 m) span 20 ft (6.1 m) parallel to the exterior walls and support a beam at midspan. The two-directional framing of this system embodies alternate load paths that are important to the response of the structure in the 9/11 crash.

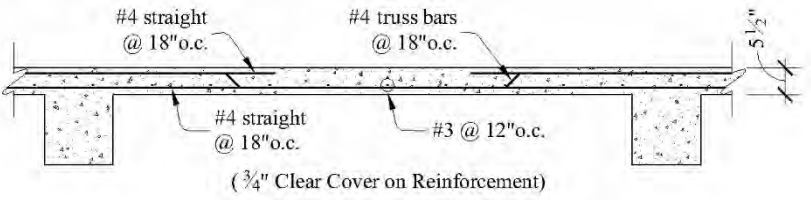

Figure 4. Typical floor slab (to convert inches to meters, multiply by 0.0254).

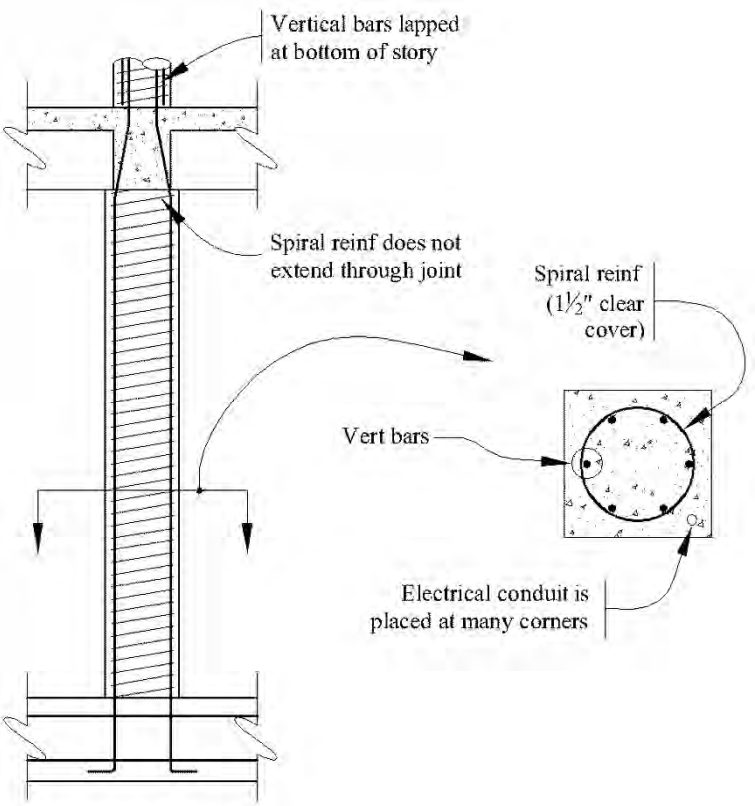

Figure 5. Typical column (to convert inches to meters, multiply by 0.0254).

Figure 4 shows the details of the floor slabs in the area of interest for this study. Note the use of straight and trussed bars. Approximately half of the bottom bars are made continuous by laps of 30–40 bar diameters at the supports. The longer spans generally have approximately equal areas of steel at the critical sections. The details of the beams and girders contain similar continuity of reinforcement through their supports. All of this continuity will be a significant factor in the response of the structure to the 9/11 crash.

Most columns were square, as illustrated in Figure 5. The sizes generally varied from about 21 by 21 in. (0.53 m) in the first story to 14 by 14 in. (0.35 m) in the fifth story. Nearly all the columns that support more than one level were spirally reinforced. This feature is crucial in the response of the columns on 9/11.

As the Pentagon approached 50 years in service in the late 1980s, planning for a substantial renovation began. The goal was a modern facility built to last another 50 years. The majority of the work addressed outmoded architectural, electrical, and mechanical features. In addition, the windows and supporting components were upgraded to provide a measure of resistance to extreme pressure.

The renovation is proceeding serially by five apex-centered wedges. On September 11, 2001, the renovation of the first wedge was nearing completion and preparations for the renovation of the second wedge were beginning. The impact of the aircraft was near the boundary of these wedges and inflicted damage in both of them.

3. The 9/11 Crash

The impacting airplane was a Boeing 757-200 aircraft whose overall dimensions are shown in Figure 6. When the aircraft departed from Washington's Dulles International Airport on the morning of September 11, 2001, it held 64 passengers and crew members.

According to the National Transportation Safety Board, the aircraft weighed approximately 181,520 lb (82,000 kg), of which 36,200 lb (16,400 kg) was fuel at the time of impact. It was traveling at 460 knots (240 m/s) on a magnetic bearing of 70° when it struck the Pentagon.

According to Boeing engineers, much of the aircraft fuel was contained in the wing tanks. The weight in each wing consisted of the following:

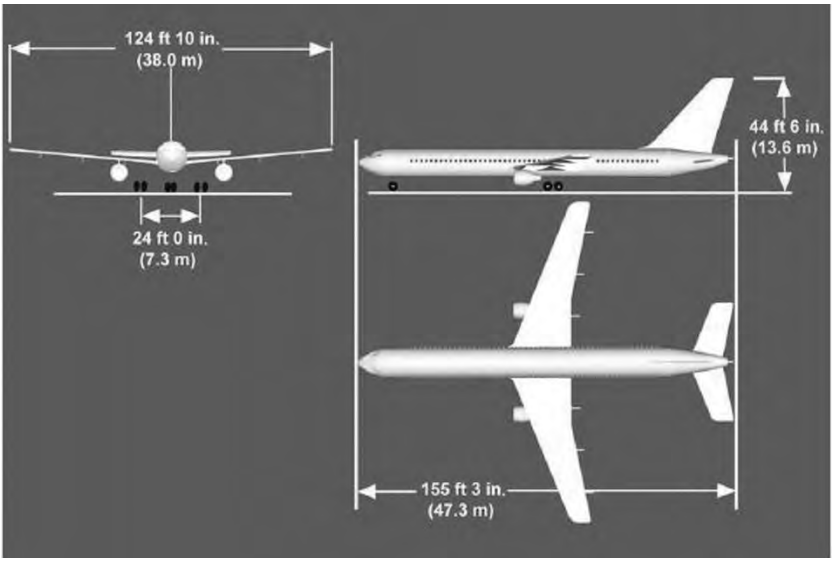

Figure 6. Dimensions of Boeing 757–200 aircraft.

Exposed wing structure	13,500 lb (6,100 kg)
Engine and struts	11,900 lb (5,400 kg)
Landing gear	3,800 lb (1,720 kg)
Fuel	14,600 lb (6,600 kg)
Total	43,800 lb (19,900 kg)

The balance of the weight was in the fuselage. In the normal course of use, the center fuel tank is the last filled and the first used.

Thus, the weight of the fuselage at the time of impact was 181,520 – (2 × 43,800) = 93,920 lb (42,600 kg). Of this, 36,200 – (2 × 4,600) = 7,000 lb (3,200 kg) was fuel in the center tank.

According to eyewitness accounts and other information, the Boeing 757 approached the west wall of the Pentagon from the southwest, as indicated in Figure 7.

It was so low to the ground that it clipped an antenna on a vehicle on an adjacent road and severed light posts. When it was approximately 320 ft (97 m) from the west wall of the building, it was flying nearly

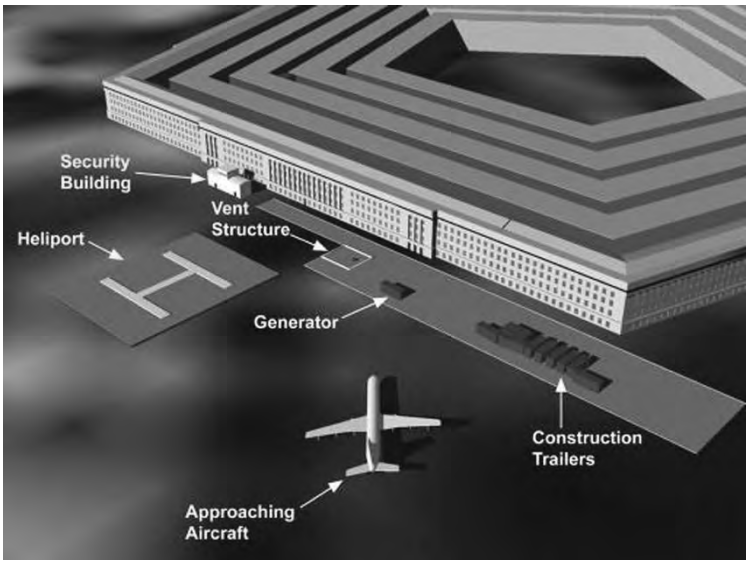

Figure 7. Pentagon and approaching aircraft.

Figure 8. Fireball within 2 s of impact.

level, only a few feet above the ground. The aircraft flew over the grassy area next to the Pentagon until its right engine struck a large construction generator that was approximately 100–110 ft (30–33 m) from the face of

Figure 9. Northern portion of impact area before collapse.

Figure 10. Ring E after collapse.

the building. At that time, the aircraft had rolled slightly to the left, with its right wing elevated. After the plane had traveled approximately another 75 ft (23 m), the left wing struck a ground-level vent structure at nearly the same instant that the nose of the aircraft struck the west wall of the Pentagon.

The impact of the fuselage was in the renovated first wedge at an angle of approximately 42° to the exterior wall. The elevation was slightly below the second-floor slab. The left wing passed below the second-floor slab, and the right wing crossed at a shallow angle from below the second-floor slab to above the second-floor slab. As shown in Figure 8, a large fireball engulfed the exterior of the building in the impact area.

Interior fires began immediately. Remarkably, the floors above the point of impact remained standing, as indicated in Figure 9.

A limited collapse in this area did occur at 19 min following the crash, as can be seen in Figure 10.

4. Damage

With the possible exception of the immediate vicinity of the entry point, essentially all interior impact damage was inflicted in the first story. The aircraft seems for the most part to have slipped between the first-floor slab on grade and the second floor. Figure 11 depicts the conditions within the building before they were disturbed by the rescue and recovery operations.

The aircraft appears to have disintegrated as it moved through the forest of columns on the first floor. As the moving debris from the aircraft pushed forward the contents and the demolished exterior wall of the building, the debris from the aircraft and building most likely resembled a rapidly moving avalanche through the first floor of the building.

As illustrated in Figure 12, the path of damage extended from the west exterior wall of the building in a northeasterly direction completely through Rings E, D, and C and their connecting lower floors.

There was a hole in the east wall of Ring C, emerging into AE Drive, between column lines 5 and 7, at a point approximately 310 ft (94 m) from where the fuselage of the aircraft entered the west wall of the

Figure 11. Interior damage.

building. Along this path the capacity of approximately 50 columns was destroyed or significantly reduced.

The impact stripped the cover off about 30 additional columns on this path. A representative example is shown in Figure 13.

While at the time of this photo shoring had been installed for the safety of search and rescue personnel, the capacity of the spirally reinforced element endured the extreme loading of the impact by itself.

As noted previously, the floors above the area of impact damage remained standing. After approximately 19 min a portion of these did collapse. However, this collapse was relatively localized relative to the extent of impact damage, as indicated in Figure 12.

In addition to the impact, the structural frame was also loaded by the fire following the crash. The damage from this generally was similar to that normally resulting from serious fires in office buildings.

This consisted of cracking and spalling in columns, beams, and slabs. The columns shown in Figure 14 exhibit such longitudinal cracks

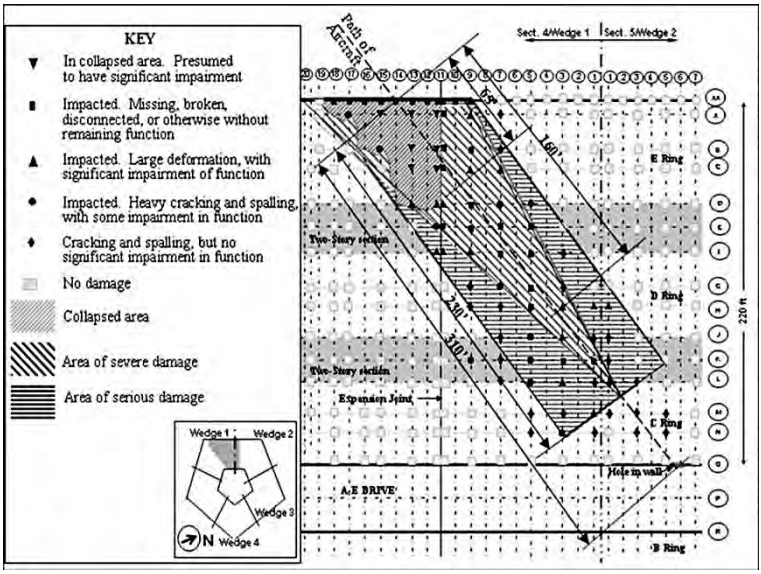

Figure 12. Damaged columns.

Figure 13. Stripped column.

Figure 14. Thermal damage to columns.

and corner spalls. In addition, some sections of the columns appeared blackened, probably as a result of direct exposure to flame caused by the partial loss of interior finishes. This fire damage to the structural frame occurred sporadically along and adjacent to the path of the aircraft.

The material properties of the concrete and reinforcing steel in the structural frame were found to be consistent with those used in the original design. For the concrete, this was determined through the compressive testing of cores and the petrographic examination of samples. For the reinforcing steel, this was established by the tensile testing of samples.

5. Analysis

The damage, detailed in the previous section, suggests three issues of structural performance that require analysis. First, the impact of the aircraft laterally loaded a large number of spirally reinforced columns. The response ranged from complete removal to inconsequential damage.

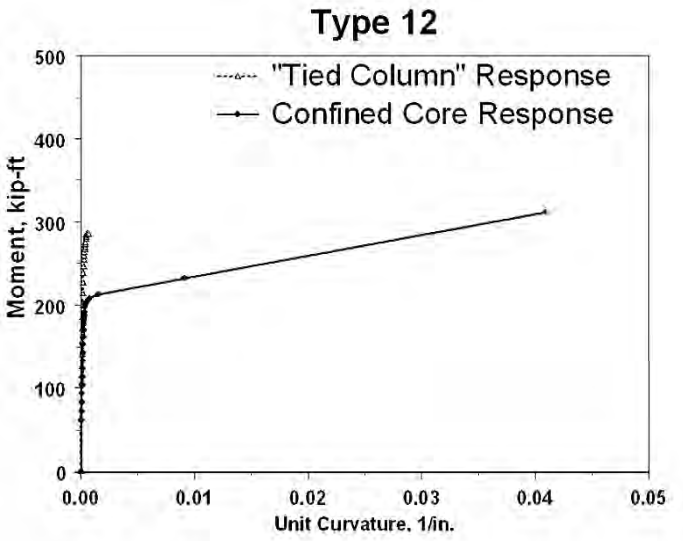

Figure 15. Lateral response of column (unit conversion factors are as follows: multiply kip-foot by 1.356 to obtain kilonewton-meter; multiply inch by 0.0254 to obtain meter).

Second, a portion of the structure in which many of the columns had been destroyed by the impact remained standing. As such performance is to be desired, the reasons for it are of interest to the engineering profession. Third, a limited collapse occurred approximately 19 min after the impact of the plane. This calls for an examination of the fire loading of the structure in this interval. Comprehensive analyses of these three phenomena could be performed, but the fidelity of the available input and response data is not on a par with the demands of such attempts. The following paragraphs contain quantitative data based on simple calculations to provide a perspective on the toughness of the structure and the effect of the fire.

The capacity of a laterally loaded column can be observed in its moment-curvature relationship. In particular, the area under this curve is proportional to the energy absorbed. A representative example of the Pentagon columns is provided in Figure 15.

In this calculation, the concrete and reinforcement were based upon testing of in-place material performed both for the ongoing renovation project and for the reconstruction following the attack. For the concrete

stress-strain properties, two assumptions were made—one for unconfined concrete and one for confined concrete. The first assumption was used to compute a relation based on the gross area of the square column treated as a tied column using a compressive strength of 85% of the test cylinder. The second assumption was used to develop a relation for the core of the column confined using a limiting strain corresponding to the fracture of the reinforcement. For calculating the relationship between the resisting moment and unit curvature for each type of column, an estimated service axial load was used reflecting the tributary dead load of the structure.

In Figure 15, it is apparent that the spirally reinforced concrete core absorbs considerably greater energy than that calculated for the gross section of the square "tied" column with unconfined concrete. This is principally due to a higher limiting curvature. If energy absorption is a design objective, the evidence suggests that spirally reinforced concrete columns are a good choice.

The ability of the floor system to span over a large number of missing columns was examined by applying a flexural yield line analysis. Flexural capacities at critical sections were determined, ignoring the effect of compression reinforcement. It was assumed at the support sections that the tensile reinforcement in the slab acting as a flange was effective in resisting flexure. The width of the flange was defined to be equal to the clear depth of the beam below the slab. Considering the moment gradient along the span at sections where flexural yield was expected, the effective stress in the tensile reinforcement was assumed to be 5/4 times the yield stress at room temperature. The roughly 30- to 40-diameter lap of bottom reinforcement was taken to develop this higher yield in those bars at the critical locations.

An area of particular interest is the portion that remained standing after impact and collapsed after approximately 19 min. In Figure 16, the analysis of this segment was estimated by assuming that all columns at the intersections of column lines 12 through 16 and AA, A, B, and C were lost.

The assumed locations of the negative- and positive-moment yield lines are shown in the figure. The floor-system edge along line 11—the location of the expansion joint—was assumed to be unsupported. Line AA (the exterior façade) was considered to be a support for the floor system. The calculated capacity for the failure condition shown

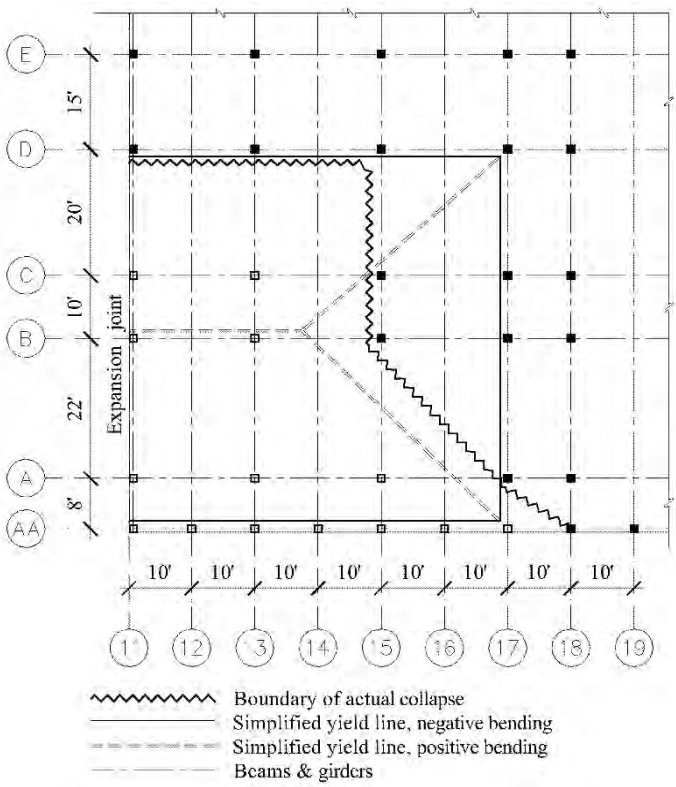

Figure 16. Yield line analysis (to convert feet to meters, multiply by 0.3048).

ideally in the figure was approximately 160 psf (7.7 kPa). Thus, for the assumed boundary, material, and support conditions, the floor system at level2 would have been able to support itself over the assumed unsupported area. It was specifically the continuity of bottom reinforcement and the two-directional framing that provided the ability to span over several missing columns.

It was hypothesized that the fire was the cause for the limited collapse that occurred approximately 19 min after impact. This premise was tested through finite element thermal analysis. This was complicated by uncertainty about the amount of concrete cover that the crash impact stripped over the reinforcing steel. Further, the fire loading was something between that of a building fire and a hydrocarbon pool Thus, a

TABLE 1. Thermal response of structural frame

Structural element	Cover condition	Fire exposure	Endurance time (min)
Column	Undamaged	Building	155
Column	Undamaged	Hydrocarbon	125
Column	Stripped	Building	50
Column	Stripped	Hydrocarbon	25
Girder	Undamaged	Building	130
Girder	Undamaged	Hydrocarbon	100
Girder	Stripped	Building	20
Girder	Stripped	Hydrocarbon	12

suite of bounding calculations was performed as delineated in Table 1. The last column contains the endurance time at which the temperature of the reinforcing steel corresponds to impending yield. From these it is plausible that the fire loading of structural elements whose concrete cover had been stripped by the crash led to the partial collapse approximately 19 min after impact.

6. Comparison to Oklahoma City Bombing

To underscore the lessons learned from the Pentagon 9/11 crash it is useful to examine the response of the Oklahoma City Federal Building in the 1995 terrorist bombing (American Society of Civil Engineers, 1996). This building (Figure 17) was a nine-story office tower that was completed in 1976. In all respects the design and construction were in complete compliance with the building codes applicable at that time.

The framing of the floor system, shown in Figure 18, consisted of a reinforced concrete slab that spanned 20 ft (6.1 m) to shallow drop beams. These in turn spanned 35 ft (10.7 m) directly to the columns. This was completely in accordance with the requirements of the building code.

However, it did not provide an alternate load path, as in Figure 3, should the unanticipated loss of a support occur. An important feature of the framing was a large transfer girder at the third floor, which allowed the removal of every other column to create larger open space

Figure 17. The Oklahoma City Federal Building. (ASCE, 1996).

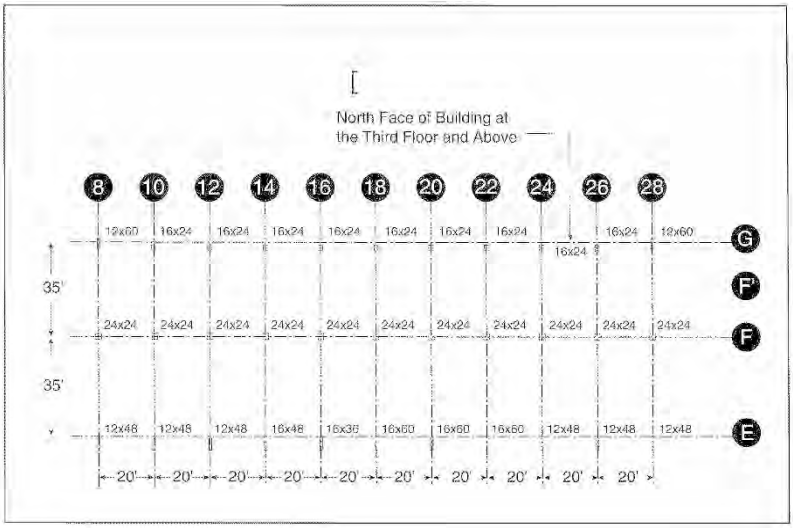

Figure 18. Structural framing (unit conversion factors are as follows: multiply foot by 0.3048 to obtain meter; multiply inch by 0.0254 to obtain meter). (ASCE, 1996).

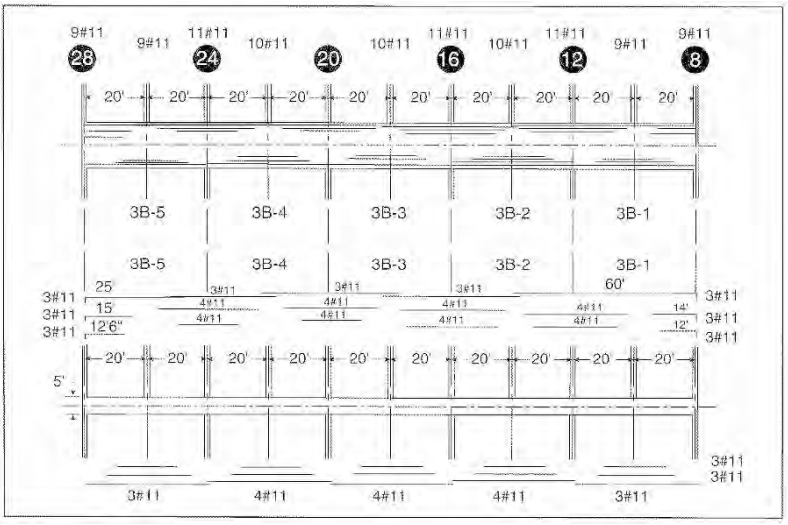

Figure 19. Girder reinforcement (to convert feet to meters, multiply by 0.3048). (ASCE, 1996).

in the lower floors. The reinforcement of this girder (Figure 19) was in full conformance with the code.

However, this detailing lacked the continuity of Figure 4, which is important should something unforeseen happen to a supporting column.

The reinforcement of these columns is shown in Figure 20. This was also in compliance with the requirements of the building standards. However, the discrete lateral ties lack the confining ability of the spiral reinforcement in Figure 5.

The terrorist bomb was detonated adjacent to one of these columns supporting the transfer girder. According to the measured crater, the energy of the bomb was equivalent to 4,000 lb (1,800 kg) of trinitrotoluene. Of course, the loading from such an event was not anticipated in the applicable building regulations of the time.

A single degree of freedom analysis of the blast response of the columns supporting the transfer girder was performed from the available information. The results summarized in Table 2 indicate that the blast likely destroyed three of the four intermediate columns. This is consistent with the damage observed following the blast.

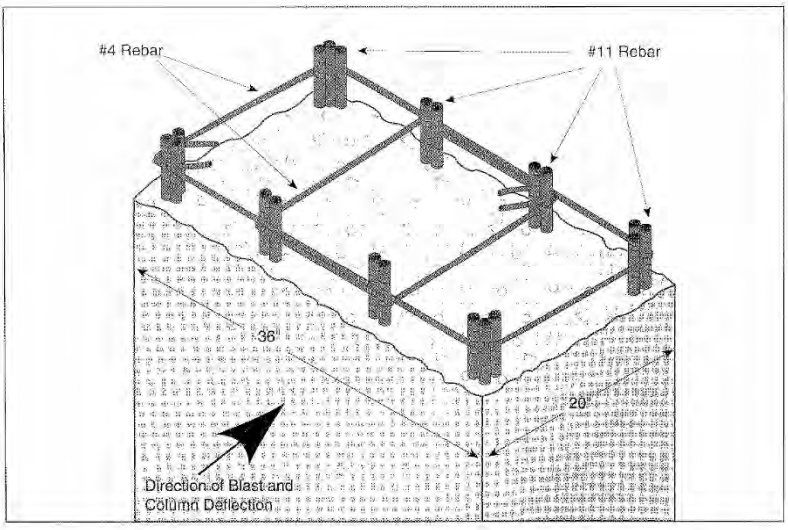

Figure 20. Column reinforcement (to convert inches to meters, multiply by 0.0254). (ASCE, 1996).

TABLE 2. Response of columns supporting transfer girder

Column no.	G24	G20	G16	G12
Range, ft	37	21	50	89
Overpressure, psi	1,400	5,600	641	115
Shear at Support/capacity	1.8	Destroyed by brisance	1.0	0.1

Note: Unit conversion factors are as follows: multiply feet by 0.3048 to obtain meters; multiply pounds (force) per square inch by 6.894757 to obtain kilopascals.

The overall damage to the building is shown in Figure 21. It is clear that the direct blast damage to the columns supporting the transfer girder led to the collapse of a significant portion of the structure. This collapse, not the direct blast effects, was the cause of 90% of the fatalities in the bombing.

7. Conclusions and Recommendations

Through observations at the Pentagon crash site and approximate analyses, the team determined that the direct impact of the aircraft destroyed the load capacity of about 30 first-floor columns and significantly

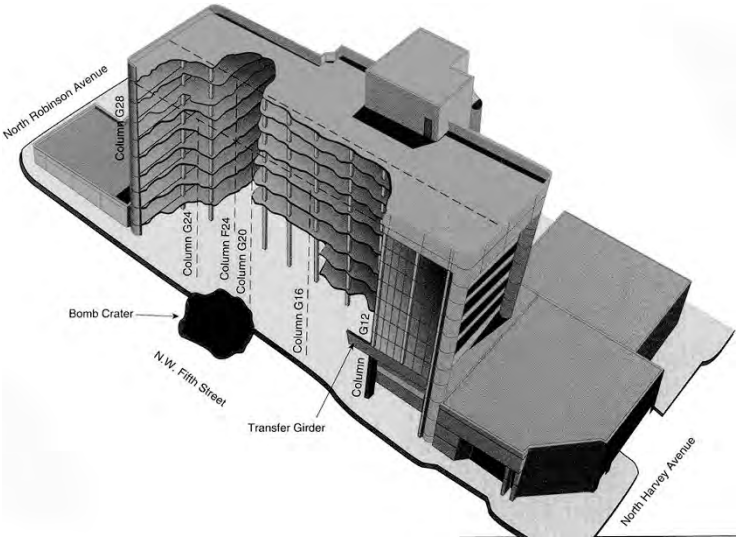

Figure 21. Bomb damage. (ASCE, 1996).

impaired that of about 20 others along a diagonal path that extended along a swath that was approximately 75 ft (23 m) wide by 230 ft (70 m) long through the first floor. While the impact scoured the cover of around 30 other columns, their spiral reinforcement con-spicuously preserved some of their load capacity. The subsequent fire fed by the aircraft fuel, the aircraft contents, and the building contents caused damage throughout a very large area. This fire caused serious spalling of the reinforced concrete frame only in a few, small, isolated areas. Despite the extensive column damage on the first floor, the collapse of the floors above was extremely limited. Frame and yield line analyses attribute this life-saving response to the following factors:

Redundant and alternative load paths of the beam and girder framing system.

Short spans between columns.

Substantial continuity of beam and girder bottom reinforcement through the supports.

Design for warehouse live load in excess of service load.

Significant residual load capacity of damaged spirally reinforced columns.

An area covering approximately 50 by 60 ft (15 by 18 m) of the upper floors above the point of impact did collapse approximately 20 min after the impact. Thermal analyses indicate that the deleterious effect of the fire on the structural frame, together with impact damage that removed protective materials and compromised strength initially, was the likely cause of the limited collapse in this region.

The Pentagon's structural performance during and immediately following the September 11 crash has validated measures to reduce collapse from severely abnormal loads. These include the following features in the structural system:

Continuity, as in the extension of bottom beam reinforcement through the girders and bottom girder reinforcement through the columns.

Redundancy, as in the two-way beam and girder system.

Energy-absorbing capacity, as in the spirally reinforced columns.

Reserve strength, as provided by the original design for live load in excess of service.

These practices are examples of details that should be considered in the design and construction of resilient structures for multiple hazards.

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AN ASSESSMENT OF A FIRE RISK FOR MULTIFUEL CAR REFUELING STATIONS

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Abstract: An assessment of an individual and social risk for multifuel car refueling stations of various types containing units with petrol, natural gas and LPG has been carried out. It has been shown that the main part of the total fire risk is given by the LPG unit. An influence of a chain development of an accident on the value of the individual risk is investigated.

Keywords: risk; fire; explosion; multifuel; car refueling station

1. Introduction

Car refueling stations (CRS) are objects with a high fire hazard. A large part of CRS are located on territories of cities, and therefore possible accidents represent a serious fire hazard to population of these cities. The fire hazard of CRS elevates remarkably in the case of presence of units with natural gas and LPG at these stations (in the case of so called multifuel CRS). Therefore a quantitative assessment of a fire risk for the multifuel car refueling stations (MCRS) is needed.

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The purpose of this work is the assessment of the individual and social risk of fires and explosions on the MCRS.

2. Method for an Assessment of an Individual and Social Risk

The individual risk is determined as a frequency of occurrence of the hazardous factors at a determined point of space, which cause a human death 1.

The individual risk R (year^{-1}) of fires and explosions on external technological installation is described by a formula (Shebeko *et al*., 1995, NPB 105-03, 2003):

$$R = \sum_{i=1}^{n} Q_i Q(A_i), \tag{1}$$

where n is a number of the considered scenarios of a development of an accident; $Q(A_i)$ is a frequency of a realization of the ith scenario, year^{-1}; Q_i is a conditional probability of a human death at the realization of the ith scenario.

In order to calculation the fire risk a territory of MCRS is divided on several zones, and inside each zone the value of R is accepted to be constant.

The probabilities of a human death Q_{ij} inside the jth zone at a realization of the ith scenario is calculated by an expression:

$$Q_{ij} = 1 - \prod_{k=1}^{l} \left(1 - Q_k \cdot Q_{ijk}\right), \tag{2}$$

where l is a number of hazardous factors taking into account; Q_k is a probability of the realization of the kth hazardous factor; Q_{ijk} is a conditional probability of a human death by the kth hazardous factor.

The individual risk characterizes a risk distribution in space (Marshall, 1987). But in some cases it is important to assess not only frequency of occurrence of the hazardous factors, but also scales of probable consequences. Concept of a social risk is used for this purpose. For example, the identical objects within and without a city will have identical distributions of the individual risk, but various levels of the social risk.

The social risk is a frequency of occurrence of accidents, in which a number of fatalities is not less, than a given one.

The social risk S (year^{-1}) for accidents with fires and explosions can be determined by a formula:

$$S = \sum_{i=1}^{n} Q(A_i), \tag{3}$$

where n is a number of the scenario, for which $N_i \geq N_0$; N_i is a the fatalities number for the ith scenario; N_0 is a critical fatalities number, for which the social risk is evaluated.

The expected fatalities number at a realization of the ith scenario can be calculated by an expression:

$$N_i = Q(A_i) \sum_{j=1}^{m} Q_{ij} n_j, \tag{4}$$

where m is a number of impact zones which are taken into account; n_j is an average population number in the jth zone.

The described method was used for the assessment of the individual and social risk for two typical MCFS. In the first case the station is used for refueling of cars with two kinds of fuel (natural gas (NG) and petrol). In the second case the station is used for refueling with three kinds of fuel (NG, LPG, petrol).

For calculations of the individual risk R (year^{-1}), it is necessary:

- To determine frequencies of initiating events connected with a release of hazardous substances into atmosphere for possible accidents
- To create event trees for an occurrence of the initiating events
- To determine probabilities of an accident development according to various branches of the event trees
- To determine conditional probabilities of a human death at a realization of the various branches of the event trees.

A frequency of a rupture of the equipment can be determined by means of statistical data or by an expert estimation. The conditional probability of a human death at a realization of various branches of the event trees were defined by means of probit – functions (Shebeko *et al*., 1995, NPB 105-03, 2003, Pietersen, 1991).

If the necessary statistical data for calculations of the frequencies of the events are absent the values of these frequencies for the various scenarios of accidents can be estimated by a formula:

$$Q(A_i) = Q_{AC} \cdot Q(A_i)_{ST}, \tag{5}$$

where Q_{AC} is a frequency of the initiating event (hazardous substance release into the atmosphere); $Q(A_i)_{ST}$ is a probability of the accident development according to the *i*th branch of the event tree, which can be taken from literature (Shebeko *et al*., 1995).

The probability of transition of accident on further stages was determined as probability of a failure of fire prevention and fire protection tools which can be taken from (Russian Fire Standard 12.1. 004-91; Shevchuk *et al*., 1995; Russian Fire Standard 12.3.047-98; Burdakov and Chernoplekov, 1990).

The basic impact factors which occur during the considered accidents are:

- Overpressure in a shock wave at vapor cloud explosions or at a vessel rupture as a result of an action of a fire on this vessel (BLEVE).
- Thermal radiation from a torch, pool fire or fireball
- Projectiles formed at a destruction of vessels
- Hot combustion products at an occurrence of a flash fire.

An occurrence of a flash fire or a vapor cloud explosion is possible only at a formation of a vapor cloud. This process is controlled by such factors as an area of evaporation from a liquid pool, sizes of formed vapor cloud and time of delay of ignition8.

In calculations, a value of a volume specific pool area was accepted to be equal 0.15 $m^2\ l^{-1}$ (Shevchuk *et al*., 1992). The mass specific pool area is equal to 0.21 $m^2\ kg^{-1}$ for petrol, 0.19 $m^2\ kg^{-1}$ for diesel oil, 0.28 $m^2\ kg^{-1}$ for LPG. It was accepted that 40% of the released LPG is evaporated instantaneously, and other 40% LPG is evaporated from droplets, and only 20% of the released LPG forms a liquid pool (Burdakov and Chernoplekov, 1990). The intensity of evaporation of petrol from a pool was calculated for temperature equal to 45°C (the possible highest temperature in Russia (Russian Building

Standard SNIP 23-01-99)). The delay time of an ignition source was estimated on statistical data (Burdakov and Chernoplekov, 1990).

The radius of the zone in which impact is formed by a flash fire was accepted to be equal:

$$R = E^{1/3} \cdot X_{LFL}, \tag{6}$$

where E is volumetric coefficient of extension of combustion products (for hydrocarbons $E \approx 7$); X_{LFL} is a radius of a zone restricted by fuel vapor concentration on the level of lower flammability limit.

The conditional probability of a human death in the area occupied by combustion products in the case of a flash fire was accepted to be equal to 1 (Clay *et al*., 1988).

3. Results and Discussion

The dependence of the individual risk on distance for two types of MCRS are presented in Figure 1 below (solid line—risk for MCRS with the LPG unit; dashed line—risk for MCRS without LPG unit) and in Figure 2 (solid line—data for MCRS with the LPG unit with the account of the chain development of accidents; dashed line—data for MCRS with the LPG unit without the account of the chain development of accidents).

The risk values for two types of MCRS are close to each other at low distances. It is caused by the fact that the most significant contribution to the risk value is made by accidents with petrol and diesel fuel because these accidents have rather high frequencies, but low sizes of the impact zones.

With an increase of a distance from the object the risk for MCRS with presence of the LPG unit is much higher than risk for MCRS containing NG and liquid motor fuel. This is caused by the large radius of the impact zone for accidents with fires and explosions on the LPG unit.

It is interesting to consider the contribution of a chain development of an accident in terms of the risk values. The chain development is a sequence of events, when various technological equipment is sequentially involved into the accident. Such chain development of the accident can cause large material damage and human death.

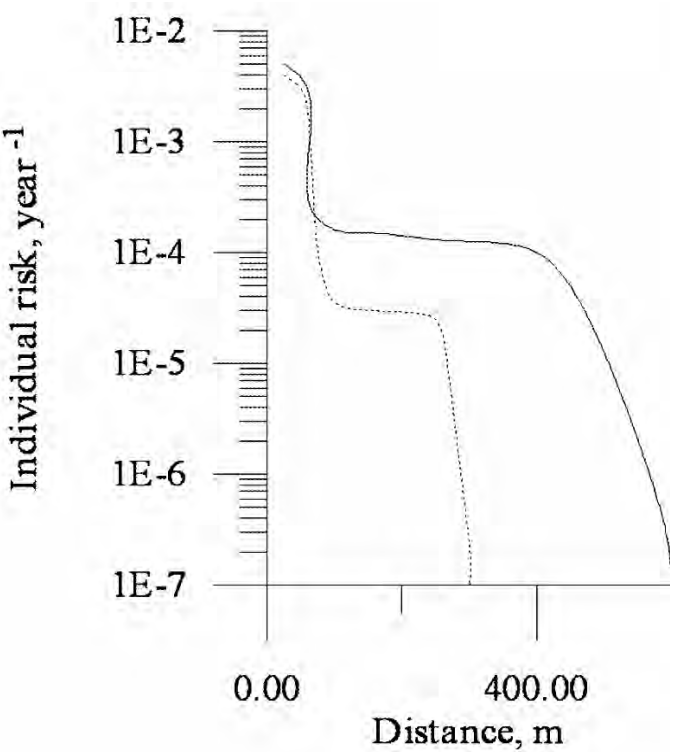

Figure 1. Individual risk upon distance from multifuel refueling station for two types of MCRS. (Solid line—risk for MCRS with the LPG unit; dashed line—risk for MCRS without LPG unit).

The greatest hazard arises at a transition of accident in the technological unit with LPG. The dependence of the individual risk with and without account of the chain development of the accident are shown in Figure 2. It is evident that the chain scenario is the most important at small distances from a place of failure. It is important to consider a chain development of accidents for the risk assessment, particularly for facilities with LPG.

For an assessment of the social risk we considered three zones with various population densities (Shebeko *et al.*, 1995; Shevchuk *et al.*, 1997).

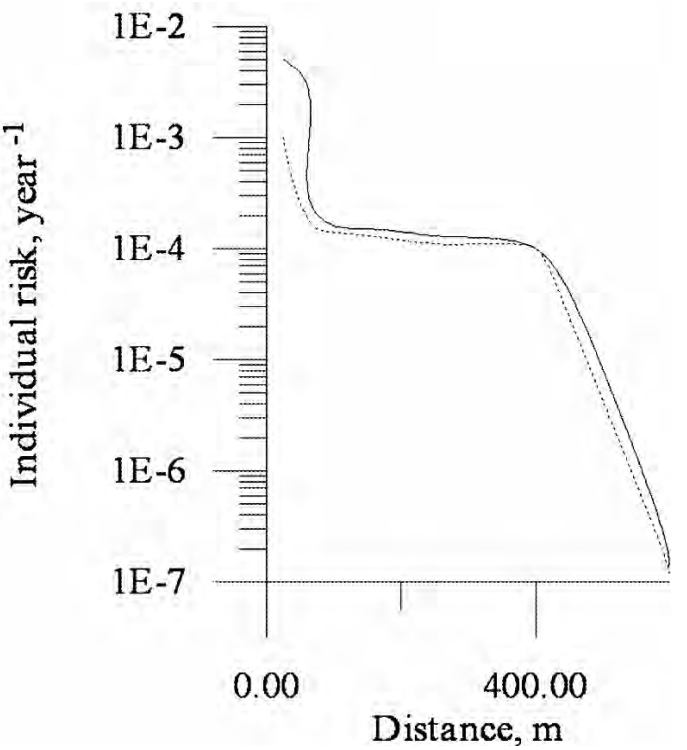

Figure 2. Individual risk upon distance from multifuel refueling station with the LPG unit. (Solid line—with the account of the chain development of accidents; dashed line—without the account of the chain development of accidents.)

Zone A is a territory of the so called industrial zone of CRS where a car refueling takes place. It was accepted, that the average number of people in this zone is equal to 10.

Zone B is a zone of service of passengers and drivers (shop, cafe etc.). It was accepted, that the average number of people in this zone is equal to 30.

Zone C is a city zone. It was accepted, that the density of the population in this zone is approximately 2,000 km^{-2}.

The social risk for MCRS containing units with NG, LPG and liquid motor fuel is equal to the following values.

1. If $N_0 \geq 1$ the value of the social risk for the personnel of the station, drivers and passengers it equal to $8 \cdot 10^{-3}$ year^{-1}, and for people outside the station—$1.7 \cdot 10^{-3}$ year^{-1}.
2. If $N_0 \geq 10$ the value of the social risk for the personnel of the station, drivers and passengers is equal to $5 \cdot 10^{-3}$ year^{-1}, for people outside the station—$1.2 \cdot 10^{-4}$ year^{-1}.

The social risk for MCRS containing only NG and liquid motor fuel is equal to the following values.

1. If $N_0 \geq 1$ the value of the social risk for the personnel of the station, drivers and passengers is equal to $6.5 \cdot 10^{-3}$ year^{-1}, and for the people outside the station—$1.3 \cdot 10^{-3}$ year^{-1}.
2. If $N_0 \geq 10$ the value of the social risk for the personnel of the station, drivers and passengers is equal to $4.8 \cdot 10^{-3}$ year^{-1}, for people outside the station—10^{-5} year^{-1}.

The quantitative assessment of the individual and social risk of fires and explosions for MCRS made in this work is, in our opinion, assessment of the upper bond of their values (i.e. the values of the risk are probably overestimated). It is explained by an insufficient experience of the operation of such objects and absence of the reliable statistical information about accidents on MCRS. Therefore the frequencies of occurrence of emergencies were assessed as a result of an expert estimation. However, on the basis of the obtained data it is possible to make a conclusion, that the fire hazard of such objects without additional protective measures is inadmissibly high.

From the analysis of the obtained results it is obvious, that for some scenarios of an accident development (especially with a participation of a car for fuel transportation, and a tank with LPG) a radius of action of the hazardous factors of fires and explosions can reach in some cases the city zone. In these cases there is a possibility of defeat of a significant number of buildings and structures. Such accidents cause a large number of human deaths and high material damage. The frequencies of initiating events for these accidents are rather small. However, the analysis of the development of other hazardous situations has shown, that the chain development of failures involving car tanks with LPG, petrol or diesel fuel and accumulators with natural gas in the accident has a noticeable probability. Though such events did not take

place in practice at an operation of MCRS, however they should be taken into account at estimation of the individual and social risk.

The largest part of the possible scenarios of accidents, beginning on units with petrol and diesel oil, concerns the high probability causes of failure of the equipment with LPG and natural gas. Accidents on these facilities are characterized by higher hazard for people because of a large density of the equipment (vessels under high pressures), and high probability of a formation of vapor clouds at a release of fuel from the tanks. These are reasons for high values of the individual risk by fires and explosions. The situation is complicated by the presence of buildings for service of drivers and passengers, promoting concentration of people on the territory of MCRS. As a consequence, social risk is also rather high.

The analysis of the risk of fires and explosions on MCRS shows a necessity of development of additional protective measures, aimed on decrease of frequency of occurrence of accidents and on prevention of their possible development.

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QUANTITATIVE RISK ASSESSMENT OF AIRCRAFT IMPACT ON A HIGH-RISE BUILDING AND COLLAPSE

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Abstract: A quantitative risk assessment method was developed to determine individual and societal risk to people living and working in high-rise towers, subjected to air. First the generalized method is described. The method takes as inputs phenomenological models of aircraft impact, explosion and fire threats to the building beside the factors characterizing environment and conditions of the incident. As a next step a simplified version is presented and an example given inspired by the WTC buildings disaster in New York in 2001. A ranking order of risk contributing factors is given and recommendations listed for risk reduction. Finally recommendations are made for continued development of the method, since this work can only be considered as preliminary.

Keywords: quantitative risk assessment; aircraft; crash; high-rise building

1. Goals and Tasks

The Dutch-Russian project (NWO# 047.014.022), comprising the work presented here, was initiated shortly after the attack on the WTC towers in Manhattan, New York on 9 September 2001 (Kirillov and Pasman, 2004). One of the goals of project was to develop a model for assessment of quantitative criteria of risk for people residing in a

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high-rise building subjected to aircraft impact and ensuing fire and building collapse.

The methodology of quantitative risk assessment (QRA) is widely used for assessment of threat level for staff and population in case of industrial accidents.

In the event of an aircraft colliding on a building (Aircraft-Building-Crash—ABC), the losses originate from a large number of factors. Some of the factors have a probabilistic nature. Present study is first of all directed on determination of the risk for people residing in the building. However in general extension of the methodologies to include risk of structural losses is possible.

The main tasks of this work can be formulated as follows:

- Developing an generalized model for QRA of ABC incident
- Developing a simplified derivative
- Risk assessment for selected high-rise building prototype
- Developing practical recommendations for risk level reduction.

2. ABC Scenarios

2.1. THE ABC STAGES

From the point of view of QRA, the phenomena occurring under ABC can be divided into two phases (Panteleev and Lukashevich, 2004):

Stage 1 "Strike"—starts from the moment of impact, ends at the moment, when dynamic influence of the aircraft, of the wave of liquid fuel and of the primary flash fire of the fuel-air mix on building and people is exhausted. This stage takes a few seconds. At this stage structural damage occurs under the action of the impact. Collapse of the building is the worst potential event at this first stage.

Resulting damage is mainly defined by the parameters of the plane (including flight parameter), design of the building and by people allocation on the floors. The key question to solve is what is a probability of "instantaneous" collapse? In that case potential human losses are equal to the number of people in the building.

Further important questions are:

- "Floor by floor" losses at/near impact area
- The conditions of evacuation routes after the strike
- Changes of the building structure and their consequences for fire resistance of the building, and for fire and smoke propagation
- Additional fire loading from aircraft contents and the spatial distribution of fuel.

Stage 2 "Evacuation"—starts from the beginning of sustained fire and ends at localization of the fire or at the end of evacuation or at the secondary collapse of the building.

The key questions for this stage are:

- Time to blocking of evacuation routes
- Time to total collapse.

Important problems to solve for this stage are:

- Propagation of fire hazard factors (smoke, temperature, low oxygen level)
- Evacuation dynamics.

In Figure 1, an event tree, focused on for human losses in the building, is presented.

We can conclude that the processes of ABC are characterized by complexity and ABC risk assessment is a rather complicated task requiring a multidisciplinary approach and a team of different specialists.

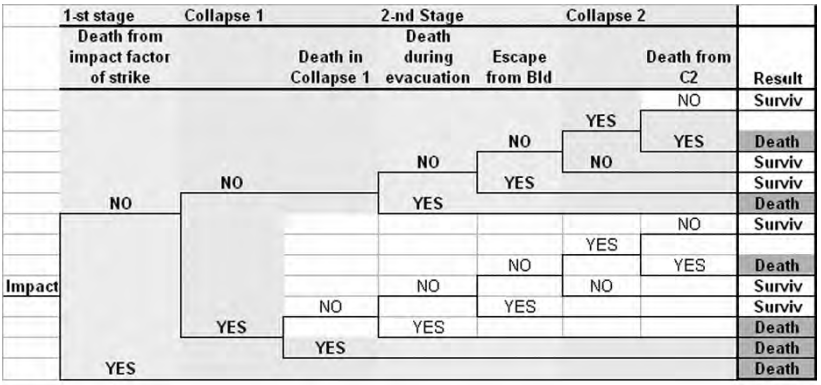

Figure 1. Event tree of human losses in the building.

2.2. SPECIFICS OF RISK ASSESSMENT FOR ABC

In most simple form, the QRA procedure for industrial objects includes the following steps:

- Preparing of the set of initial events (aircraft parameters, flight conditions, probability value estimates etc.)
- Preparing of the set of external conditions (distributions of population, climate data and lay-out and siting of building).
- For selected scenarios the following values are calculated:
  - Probabilities of initial event combinations and external conditions
  - Distribution in time and space of hazard threats
  - The consequence of impact
- Calculation of the risks for a given scenario set.

The main obstacle for application of the usual methods and programs for risk assessment is that consequences of each disaster scenario are calculated in one step for a final stage. Losses in follow-on stages, for instance as a result of secondary fire, are as a rule not considered. In commonly used methods and software, the domino effects are declared for obvious cases. The effects are accounted for qualitatively and not included in the calculation.

Here it is required to take into account for ABC the following:

- A 2-stage process of the accident in case of sufficient resistance of the building to survive after the direct effects of impact
- High concentration of people under conditions of restricted evacuation possibilities
- Unpredictability of the building state dynamics under conditions of fire spreading and restricted evacuation possibilities at the second stage of the ABC accident.

In general, procedure of QRA for ABC is similar to above mentioned industrial accident risk assessment. However, attempts to use well-known QRA software have shown that particularities of ABC do not allow using directly the known models and software being used in the world for QRA of fire-explosive and chemical dangerous objects.

The above mentioned peculiarities call for developing a special model for QRA taking into account proper ABC characteristics.

2.3. THE QUANTITATIVE RISK EXPRESSIONS

Since it does not make sense to estimate the frequency of an attack, risk is expressed as the chance to be killed being inside the building. Following to traditional risk analysis, the following definitions were made:

R_i—individual risk to be killed floor-by-floor (probability per strike);

$R_{i,\ \text{average}}$—average individual risk in building (probability per strike);

R_{soc}—societal risk (expected fatalities per strike);

P(N)—F–N curve of possible fatality loss, in which *F* is cumulative frequency of *N* or more fatalities.

In future studies, the models will be elaborated to include factors characterizing people such as age, level of readiness for emergency situations etc.

3. Generalized Model of Risk Assessment for ABC

3.1. MAIN REQUIREMENTS

Main task is the creation of a model of QRA specifically for ABC conditions, which allows the use of knowledge of experts in physical phenomena in quantitative risk assessment relating to people exposed.

In the proposed model, the aircraft strike is taken as initial event. It is expected that a plane of a certain type hits a given building with a known distribution of people on the floors. The probability of a "miss" is not considered. It is expected that models for the deterministic phenomena and events for plane and building are available.

The model for quantitative risk assessment under ABC (QRA-ABC) should have the following features:

- To provide the necessary quantitative criteria of the risk estimation with specific of ABC
- To start from using the simplest models of phenomena to get reasonable approximations for risk assessment results

- To have the possibility of development by including new models of the processes and phenomena with accumulation of the knowledge and data
- To permit the expansion of the amount of variables and parameters take into account
- To using for high-rise buildings of different design.

These can be simple to start with very simple sub-models but the QRA-ABC model shall allow more sophisticated models of the phenolmena to be inserted later.

3.2. EQUTION SET OF GENERALIZED MODEL OF QRA-ABC

Since probability of death as a result of the hazard factors under ABC is very high, it is impossible to use the simplified form for expression of the total risk as the amount of summarized risks from separate events. Instead the product of probability of survivals on each stage shall be used. Taking this into account and also the two stages of ABC defined above, the main risk quantities of QRA can be expressed as follows:

The individual risk for the *i*th floor:

$$\mathrm{R}_i = \sum_{n=1}^{Nst} \sum_{k=1}^{Ncl} \sum_{m=1}^{Nb2} \mathrm{P}\,sc_{nkm}\,\mathrm{Pd}_{inkm}$$

The societal risk:

$$\mathrm{R}\,sc = \sum_{n=1}^{Nst} \sum_{k=1}^{Ncl} \sum_{m=1}^{Nb2} N_{nkm}\,\mathrm{P}\,sc_{nkm}$$

Probability of death:

$$\mathrm{Pd} = 1 - \prod_{j}^{2} (1 - \mathrm{Pd}_j)$$

Here, i is the floor number (storey index); n is the type of strike; k is the type of "instant" (partial) collapse; m is the type of building condition in the 2nd stage; Pd_j is the probability of death for different stages of accident; Psc_{nkm} is the probability of n-type strike realization, "instant" k-type collapse, and m-type building condition in the 2nd stage; Pd_{inkm} is the probability of death on the ith floor during n-type strike, "instant" k-type collapse, and m-type building condition in the 2 stage; and N_{nkm} is the number of victims in building during n-type strike, "instant" k-type collapse, and m-type building condition in the 2nd stage.

Some comments:

"type of strike n-type" in the general case is a complex of parameters—number of the floor at which aircraft impacts, aircraft velocity, angles of hit, mass of fuel;

"k-type of instant collapse on 1st stage" in the general case is the possibility of partial or total building collapse immediately after the strike;

"building condition m-type on 2nd stage" in the general case is comprehended as a complex of parameters characterizing the building after collapse—quantity and time of blocking of evacuation routes, time duration of delay of further collapse;

for each incident variant we have to get its probability (Psc_{nkm}) and the number of deaths (Pd_{inkm}).

For providing the quantitative risk computations it is necessary to develop the following phenomena models:

Pst_n = F_Pst_n—probability of n-type strike[†];

$Pd1_{in}$ = F_$Pd1_{in}$—probability of death on the ith floor for n type strike on the first stage;

$P1c_{nk}$ = F_$P1c_{nk}$—probability of type k collapse on the first stage of n-type strike;

$Pd1c_{in}$ = F_$Pd1c_{in}$—risk on ith floor for n-type strike for first stage collapse of k-type;

$Pb2_{nkm}$ = F_$Pb2_{nkm}$—probability of building state in m-type condition for n-type strike (on 2nd stage);

[†] Notation F_ means variable(s) dependent function

$Pd2_{inkm}$ = F_Pd2_{inkm}—risk on *i*th floor for *n*-type strike and building condition of *m* type.

The development of the appropriate models specified above will in general solve the problem of QRA for ABC.

4. Requirements on Deterministic Models of Phenomena

It is necessary to note that work on improvement of QRA-ABC must go in iterative way from simple to complex. For the suggested model of QRA-ABC the amount of parameters taken into account for separate phenomena is not important. It can be increased with growth of understanding of hazardous phenomena. It's important to underline that computation models used in QRA must correspond to the available computer resources, because the volume of calculation increases geometrically with including new variables:

$$Ncalc = \prod_{Npar} Ngrad(i)$$

where *Ncalc* is the number of computations; *Npar* is the number of parameters; and *Ngrad* is the number of gradations for parameter *i*.

Already for the simplest case, when there are only two parameters—a number of floors and number of the pathways to evacuation, it is quite possible to reach the amount of phenomena models computations to several hundreds. The simplest case for 100 floors and 3 evacuation pathways brings us to 400 runs. For that purpose, the phenomenological models to be used for QRA should be simulated in seconds or in the extreme case in minutes of processor time. Besides these models shall not require profound specific materiel knowledge (toughness, hydrodynamics, etc.) from the risk analyst.

5. Simple Model of QRA-ABC

5.1. THE GOALS OF A SIMPLE MODEL OF QRA-ABC

The generalized model of QRA allows:

- To get preliminary quantitative results using the simplest models and expert opinions of physical phenomena

- To formulate requirements and tasks for modelling of selected phenomena
- To select key factors affecting risks estimation

The simplified physical models and expert knowledge can be integrated into a model of QRA. Improvement in simplified models can be easily applied to generalized QRA model without substantial changes in formulas.

5.2. SYSTEM OF MODELS FOR SIMPLE QRA-ABC

At present stage of the study, the simplest test models for separate phenomena based on expert's opinions are offered. Below it will be considered a building with the following features (Figure 2): $N1_{fl}$—bottom floor; $N2_{fl}$—top floor; $Np_i = F\_N2_{fl}$ (I)—distribution of people floor-by-floor; *Nmit*—number of evacuation routes.

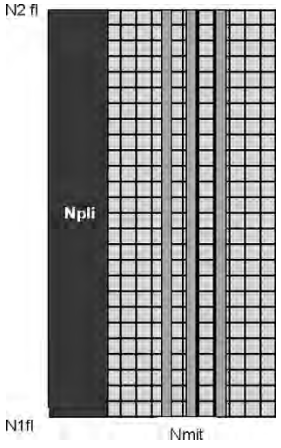

Figure 2. Geometric cross sectional plan of high-rise building.

5.2.1. *Pstn—Probability of n-Type Strike*

As strike parameter we shall consider the floor of the building on which impact takes place—*Ist.* In this case:

$$\text{Pst} = \text{F\_Pst (Ist)}, \text{Ist} = N1_{fl} \ldots N2_{fl}$$

The number of possible types of the *n*-type strike is defined only by the number of floors and “the shadow effect” from surrounding buildings:

$$Nst = N2_{fl} - N1_{flmin}.$$

As example, for a start it is logical to accept that the probability for the plane to hit below some floor N_{stmin} is equal to 0 and for all the rest of floors is uniform (Figure 3a). The more precise form of the distribution can be defined by experts.

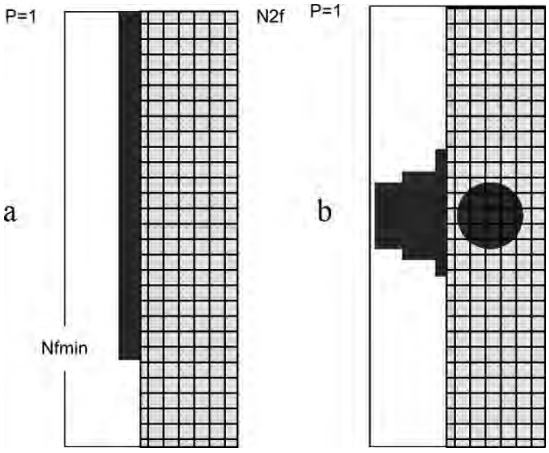

Figure 3. (*a*) Distribution of uniform probability to hit a floor above a certain lowest floor predicted by the “shadow effect” of other buildings; and (*b*) individual risk distribution at impact point in its simplest form.

5.2.2. *F_Pd1in—Probability of Death on the ith Floor Under n-Type Strike in Stage 1*

From ABC experience, computation and expert estimation of first stage damage caused by mechanical impact of the aircraft, flash fire of sprayed fuel and debris follows that death of people is possible on several floors above and below the floor of the strike. According to the expert assessments, the probability of death will be very low +/– 5 floors up and down from floor of strike due to hazard factors on the strike stage.

In this case, the risk as a function of the floor I, on which a person is located relative to floor *Ist*, is:

$$Pd1_{in} = F\_Pd1(I, Ist)$$

Hence, the simplest model for the $R1_{in}$ distribution is shown in Figure 3b.

5.2.3. *F_P1cn—Probabilities of Collapse in Stage C1 Under n-Type Strike*

The function F_P1c_n depends on the properties of the strike and features of the building construction. In our case, the only variable is the number of the floor affected by the strike *Ist*, so:

$$P1c_n = F\_P1c_n(Ist)$$

As the simplest approximation, a linear decreasing with altitude can be chosen for probability distribution of collapse (Figure 4a).

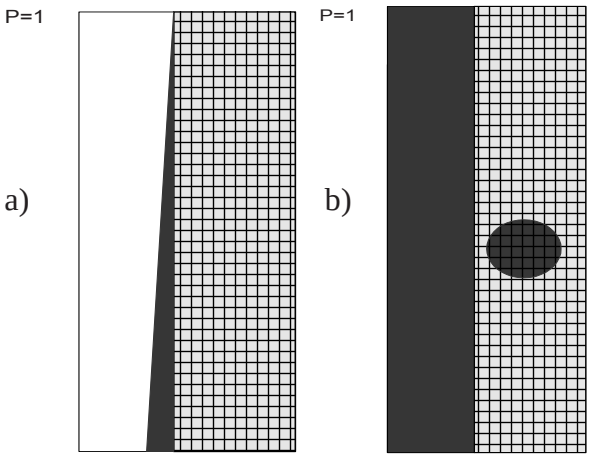

Figure 4. (*a*) Linear probability distribution of collapse at stage 1 at *n*-type strike; and (*b*) Probability of being killed at total collapse of building is near 1 independent of the floor number. The circle represents the volume of structural damage near an impact point.

5.2.4. *F_Pd1cin—Probability of Death on ith Floor During n-Type Strike in the First Collapse Stage*

The probability of survival under collapse depends on the strike and selected floor. Generally speaking the probability to survive at full collapse of buildings is negligible small, but for the general case:

$$Pd1c_{in} = F\_Pd1c_{in}\ (I, Ist)$$

As a first approximation, it is possible to expect that in case of collapse (Figure 4b):

$$Pd_{in} = 0.999$$

We will see later that there will be a more optimistic dependency as a result of only partial crushing of the building structure.

5.2.5. *Pb2nkm = F_Pb2nkm—Probability of Building State in m-Type Condition for n-Type Strike (in 2nd-stage)*

At an initial stage of the study, the distribution of $Pb2_{nm}$ can also be kept quite simple: The state of the building in this case is defined by the time evacuation pathways are being blocked and the number of blocked floors above and below the floor of strike, and the time of secondary collapse due to further weakening of the building structure by fire (Figure 5).

In this case:

$Pb2_{nkm}$ = F_$Pb2_{nkm}$(tc2, tbl(*i*), Nfl+(*i*), Nfl–(*i*))

tc2—time of collapse on the second stage;

tbl(*i*)—time of blocking *i*th pathway;

Nfl(+)—number of blocking floor up from strike floor;

Nfl(–)—number of blocking floor down from strike floor.

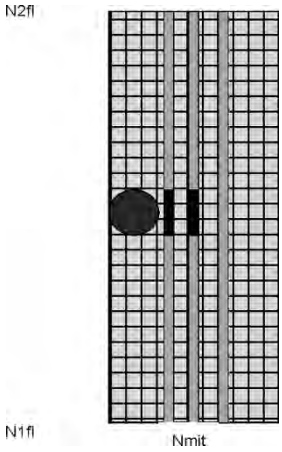

Figure 5. Graphical representation of blocked evacuation routes in the vicinity of the impact point.

$Pd2_{inkm}$ = F_$Pd2_{inkm}$—probability of death on *i*th floor for *n*-type strike and building condition of *m* type.

The risk in the second stage depends on location of the person relatively to the floor of the strike, fraction of undamaged evacuation routes, time of their blocking, time and probability of collapse in the second stage.

5.2.6. *Pd2inkm = F_Pd2inkm—Probability of Death on ith Floor for n-Type Strike and Building Condition of m Type*

The risk in the second stage depends on location of the person relatively to the floor of the strike, fraction of undamaged evacuation routes, time of their blocking, time and probability of collapse in the second stage.

If it is expected that the building is correctly designed, the probability of evacuation from floors below the point of strike is rather high, because probability of blocking of evacuation pathways is comparatively small, however there is probability to perish in jam or at collapse in the second stage.

The risk to be killed above the floor of strike depends on the undamaged pathways to evacuation. If all ways to evacuation are safe then for correctly designed building the probability to abandon the building is large, given the time to collapse in the second stage is longer than the time needed for evacuation. If all pathways are blocked it is possible to take the risk close to 1. Partial blocking will bring an intermediate value. In our case for elaboration of the model for the assessment of probability of death in the second stage let us suppose that in case time necessary for evacuation from *i*th-floor is more than the time of collapse delay in the second stage, the probability is equal to 0.999, in any other case it is equal to 0.001:

$Pd2_{inkm} = 0.999$, if $t_{evi} > t_{c2}$
$Pd2_{inkm} = 0.001$, if $t_{evi} < t_{c2}$
t_{c2}—time of delay collapse on the second stage.

Time of evacuation from the building is equal to the sum of time of evacuation from floor to floor. Let us suppose that we know the expected time of evacuation from the *i*th-floor in case all evacuation routes are in use t_{ev0i}. If part of the evacuation routes is blocked the time necessary for evacuation from floor to floor increases. In that case time of evacuation can be calculated as follows:

$$T_{ev}(I) = \sum_{0}^{I} t_{ev0}(i)\left(\frac{No(i)}{No(i) - Nblck(i)}\right)^{n_{ev}}$$

i—number of floor;
$T_{ev}(I)$—time of evacuation from *I* floors;
$t_{ev0}(i)$—design evacuation time from floor *i* to *i* – 1;
No(*i*)—number of evacuation pathways in building on floor *i*;
*Nblc*k(*i*)—number of evacuation pathways in use on floor *i*.

The suggested model allows calculating time of evacuation from each floor taking into account the time of blocking of evacuation routes and the size of the evacuation zone above and under the floor of strike. If time of evacuation from the *i*th floor is less than the time of blocking of the first evacuation route, then evacuation time is equal to the projected one. If time of evacuation from the *i*th floor is longer than time of blocking of the first evacuation route, then calculation of time is carried out according to the formula above. According to this algorithm, the time of evacuation is also calculated in case of second route blocked etc.

As a result, we can find the distribution of evacuation time from every floor for every type of strike (the floor of strike), time of evacuation, time of blocking of evacuation routes and size of evacuation zone and compare them with time of collapse in the second stage and find the probability of death for every floor in the second stage. In that case, formula for probability of death looks as follows:

$$\mathrm{Pd2}_{inkm} = \mathrm{F\_Pd2}_{inkm}\,(I\mathrm{st}, t_{c2}(m), t_{\mathrm{bl}}, N_{\mathrm{fl}+}, N_{\mathrm{fl}-})$$

where *I*st is the floor of strike; $t_{c2}(m)$ is the time of collapse in the second stage; $t_{\mathrm{bl}}(m1)$ is the time of blocking pathway, $m1 = 1\ldots N\mathrm{mit}$; $N_{\mathrm{fl}+}(m1)$ is the number of blocked floors up from strike floor, $m1 = 1\ldots N\mathrm{mit}$; and $N_{\mathrm{fl}-}(m1)$ is the number of blocked floors down from strike floor, $m1 = 1\ldots N\mathrm{mit}$.

For a simple model, we suppose that the time of collapse in the second stage has a stochastic nature and is included in the model in the probability distribution of $t_{c2.}$ The blocking time and the scale of blocking for each evacuation pathway are deterministic parameters to be produced by simple QRA-ABC models modeling the penetration of the aircraft and the damage to the building.

5.3. SIMPLIFIED MODEL QRA-ABC

The submodels described above was used for simplified models of QRA-ABC. The developed model remains possible to add to the model any necessary number of parameters characterizing strike—an angle of the attack, pitch angle, velocity of aircraft etc. In exactly the same way, it is possible to extend the number of parameters characterizing the state of building after the incident in the first stage.

In conjunction with a QRA, it is possible to use parametric and analytic engineering models. The scheme shows two classes of models of separated phenomena—models of selected individual phenomena, which are rather complex, and simple engineering models. The level of reliability of QRA results depends much on the correctness of the applied phenomena models. But already at an initial stage using the simplest models it is possible to get a quantitative value for the risk and develop some recommendation for further direction of study and risk management.

In conclusion, it is necessary to note that although the designed model is oriented on the estimation of risk to people, it can be applied for estimation of structural damages with some change.

6. Analysis of Results

6.1. DESCRIPTION OF COMPUTER PROGRAM “QRA-ABC LITE”

On the basis of a simplified model QRA-ABC a computer code “QRA-ABC LITE” code (Panteleev and Lukashevich, 2004) was written applying object oriented programming that gives an opportunity to increase, if necessary, complexity of the model without cardinal changes to the program software.

The screen of the solver is presented in Figure 6.

6.2. DESCRIPTION OF EXAMPLE

In order to assess the sensitivity of risk quantities to the main parameters of ABC, we have chosen a building analogous to the WTC building.

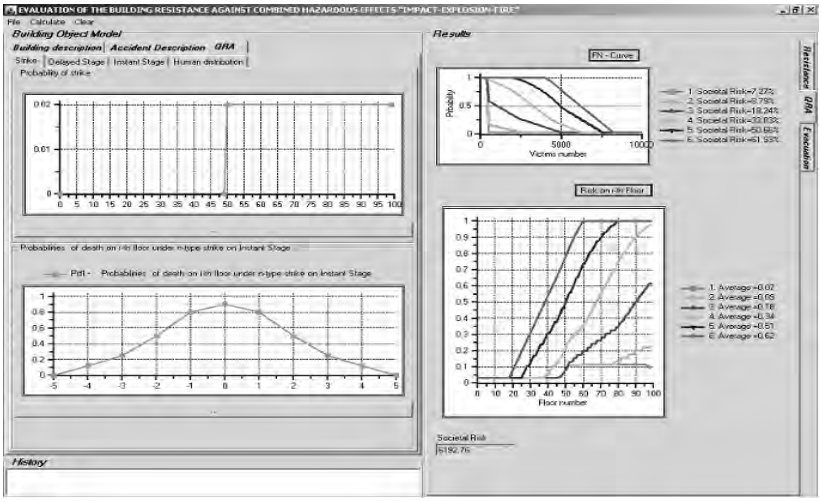

Figure 6. Screenshot of solver screen of computer program QRA-ABC LITE.

We selected the following parameter values:

- 100 floors office building
- Number of people inside the building—10,000
- Distribution of people inside the building is uniform
- Effect of “shadow” from the neighboring buildings—50 floors
- Time of evacuation from the top floor—100 min
- Basic distribution of probability of strike—uniform from 50 till 100th floor
- Probability of instant collapse in the first stage is decreasing linearly from 10% in case of strike in the 1st floor up to 1% in case of strike in the 100th floor
- Collapse probability—equal probable collapse in the period from 40 to 120 min. Probability of delayed collapse in the second stage—1.00
- Supposedly at the moment of strike one evacuation route will be blocked by the damage of aircraft impact. The 2nd evacuation route is blocked after 1 h. The 3rd evacuation route does not block until final collapse.

From the assumptions, we can conclude immediately that the main influence on fatality risk comes determined by the duration of the second stage and the evacuation rate for such type of building. It is clear that if instant and delayed collapses are impossible the main contribution to fatality risk will be by local damage at the location of impact and ensuing fire.

6.3. ANALYSIS OF INFLUENCE ON RISK BY DIFFERENT FACTORS

One of the most difficult questions of QRA for ABC is the assessment of the volume of damage around the place of strike of aircraft in the building. For this, it is necessary to take into account the following factors:

- Momentum effects by the collision
- Influence from fuel wave
- Effects due to explosion and flash fire
- Influence by debris of the building
- "Shadow" effect (aircraft can not approach to building at arbitrary angle of attack) has an essential influence on societal risk: at lower altitude of strike societal risk increases.

6.3.1. *Influence of Time of Blocking Evacuation Routes*

For the assessment of influence of the number of evacuation routes, blocked at the moment of strike the collapse delay time was supposed to be 100 min, evacuation time from 100th floor—100 min, during the evacuation stage the other pathways are not blocked. In the following calculations simultaneous blocking of all evacuation routes at certain moments was supposed. Societal risk is expressed as a percentage of the total of number of persons inside the building.

From the results presented in Figure 7 we can conclude that:

- When evacuation routes are not blocked in case time of evacuation is less than time up to delayed collapse, ABC risks are defined by the value of risks of the 1st stage.
- The value of risk above the floor of possible strike is mostly determined by time of blocking of evacuation routes.

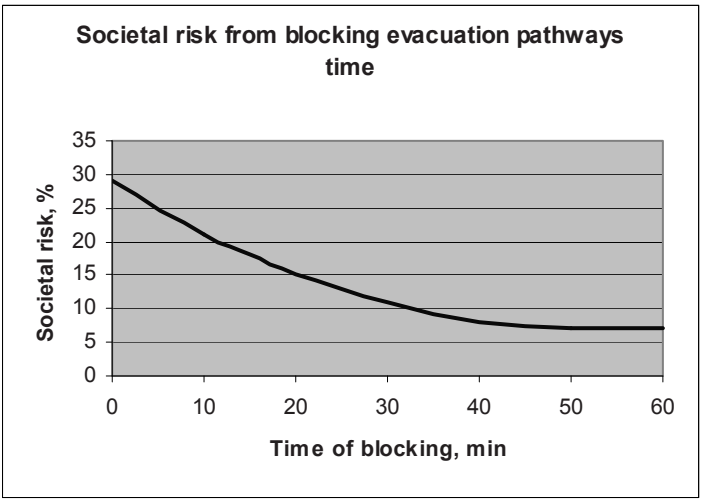

Figure 7. Influence from evacuation routes blocking time on societal risk value.

6.3.2. *Influence of Evacuation Rate*

For the assessment of influence by the rate of evacuation, we made a series of risk assessments for the basic building. Variable parameter is time of evacuation from one floor.

Results presented in Figure 8 show that evacuation time is one of the main parameters. In case evacuation time is more than time to 2nd collapse, people on the lower floors of the building can also get into the risk zone.

Most important is the ratio between time of collapse and time of evacuation. Figure 9 presents risk for different ratio of collapse time (100 min) and time of evacuation from the top floor.

In case when evacuation time for all the floors is less than time to 2nd collapse, risk value is determined only by 1st stage of the accident, namely by damage at the moment of strike and possibility of collapse due to it.

When the structure of the building is stable enough to carry the strike of the aircraft, risk is determined only by damage on the location of strike, that is small part of possible risks not more than 10% from the maximum of possible losses in case of no evacuation (for confederated type of basic building).

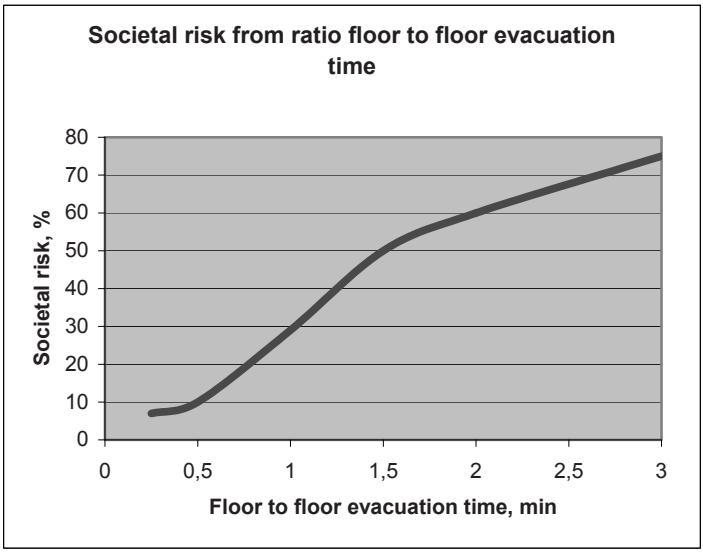

Figure 8. Influence of evacuation rate on societal risk.

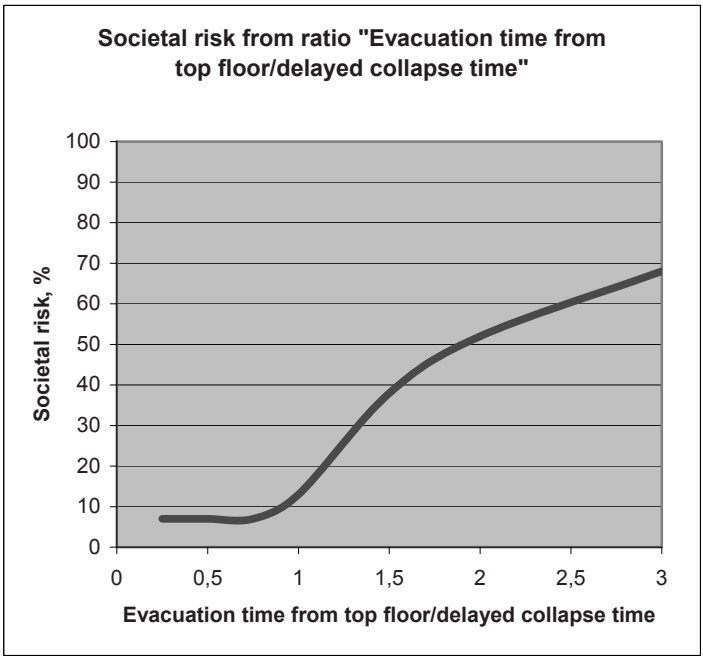

Figure 9. Influence of ratio “delayed collapse time/evacuation time” on societal risk.

6.3.3. *Influence of Time to Delayed Collapse*

For assessment of the influence of time to 2nd collapse we carried out two series of calculations. In the first series we supposed that time to collapse has an even distribution. Probability of 2nd collapse is supposed equal to 1. In the second series several moments of collapse were determined.

From the results (Figure 10) we can conclude that:

- Decrease of time to 2nd collapse essentially increases risks for upper floors
- Most significant effect has a small value of delayed collapse time.

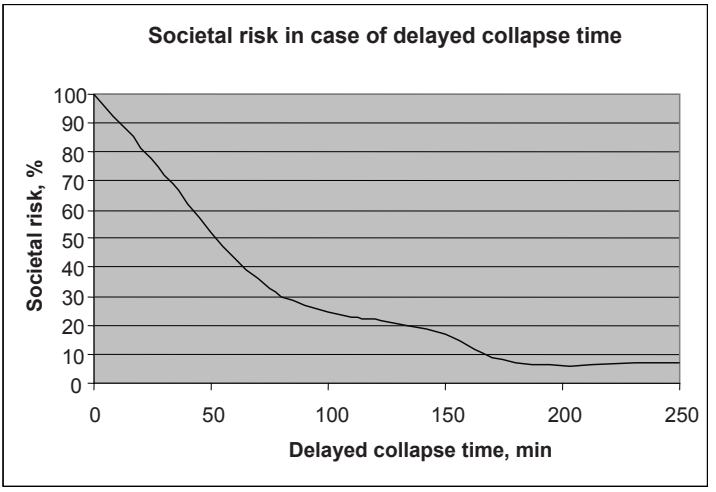

Figure 10. Societal risk/time to delayed collapse time (basic value of risk for delayed-collapse—40 min).

6.3.4. *Influence of Distribution of People Inside the Building on Societal Risk Value*

To see the influence of distribution of people on risk, a series of calculations was performed. It was assumed:

- The number of persons in the building is constant—10,000 person
- A linearly decreasing distribution of people from floors 1 to 100 with different N1/N100 ratio

From the assessments presented in Figure 11, we can conclude that:

- Obviously, decreasing the number of people on the upper floors in case of the same total number of people in the building decreases societal risk.
- Distribution of people from floor to floor is one of the most effective methods to control societal risk.

The analysis provided can build a ranking order of importance of ABC factors:

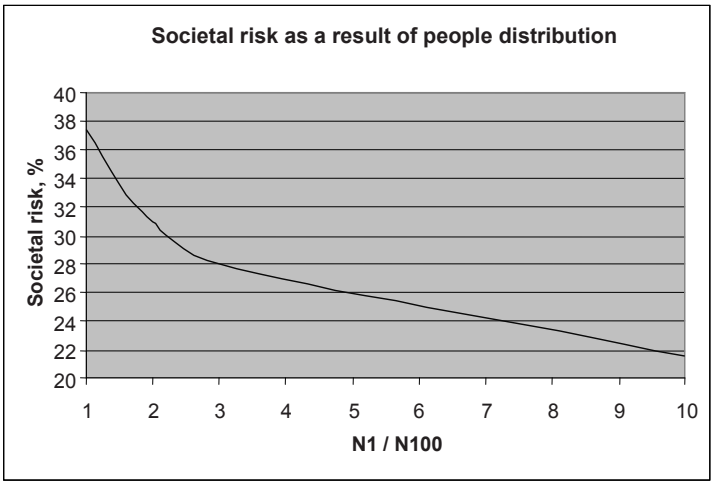

Figure 11. Influence of distribution of people over the floors on societal risk, *N*1/*N*100: 1—1; 2—2, 3—3, 4—5, 5—7.5, and 6—10.

1. Probability of "instant" collapse
2. Ratio between basic evacuation time and time to "delayed" collapse
3. Possibilities and time to evacuation path-ways blocking due to hazard effects (smoke, fire, constructive elements destruction, etc.)
4. People distribution inside the building
5. "Shadow effect" from surrounding buildings
6. Immediate effects of initial impact in 1st stage.

Although this order may also be intuitively guessed, the analysis helps to structure thought, to show differences quantified and to assist in making cost-benefit estimates of risk reducing measures.

7. Recommendations to Reduce Risk

To reduce risk, obvious measures are:

- Design of high-rise buildings must take into account the necessity not to allow collapse in the 1st stage of ABC.
- Total blocking of evacuation routes in the 1st stage by damage factors of aircraft strike, explosion, and primary flash fire or fuel flood should excluded.
- It is recommendable to plan activities such that the population density decreases with increase of floor number.
- The construction of the building must guarantee evacuation routes not to get blocked in the 2nd stage and the time duration to the 2nd collapse shall be longer than the evacuation time.

8. Recommendations for Further Research of ABC from the Risk Assessment Methodology Point of View

Presented in current report assessment of individual and societal risks in ABC allow separating the following priority tasks for further research:

1. Assessment of probability of building collapse in the 1st stage by aircraft strike and other damaging factors in the first stage according to various scenarios.
2. Assessment of probability of evacuation routes safety after the 1st stage of ABC.
3. Assessment of time of blocking of evacuation routes as a result of ensuing fires and other damage mechanisms.
4. Assessment of time duration to delayed collapse 2.
5. Development of evacuation models for high-rise buildings taking into account the specifics of ABC, particular fire and smoke generation.
6. Assessment of risk uncertainty.
7. Assessment of measures for risks reduction.
8. Assessment of cost-benefit ratio of measures.

9. Conclusions

1. A generalized model of QRA-ABC was developed which allows getting a quantified risk assessment taking into account multistage character of ABC and the complexity of processes during ABC. This model allows to take into account most of phenomena in ABC which influence the value of individual and societal risk for a given attack.
2. The generalized model of QRA-ABC can be used for different types of high-rise buildings. The model allows assessment of risk reduction measures and priority setting of recommendations.
3. In its present state and given the scarce data available, this work can only be considered as preliminary.
4. The structure of the QRA-ABC model and associated software allows to develop it further by simply increasing the number of parameters either of deterministic or of probabilistic nature.

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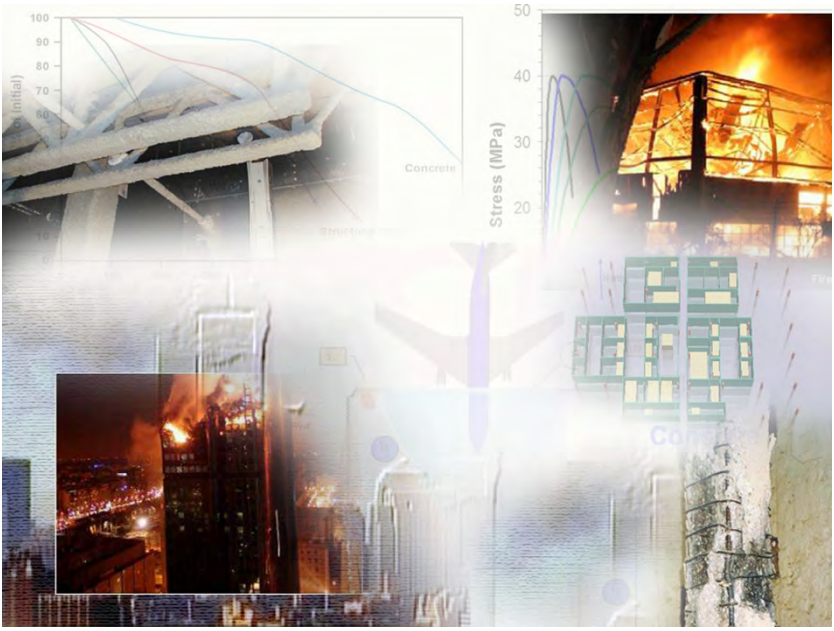
THEME 3

MATERIAL PROPERTIES, STRUCTURAL DESIGN AND TESTING



Collage by Igor Lukashevich

ENHANCING IMPACT AND BLAST RESISTANCE OF CONCRETE WITH FIBER REINFORCEMENT

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Abstract: Fiber reinforcement is undoubtedly one of the most effective means of enhancing the impact and blast resistance of concrete. Unfortunately, the dynamic properties of fiber reinforced concrete also remain some of its least understood. Since 9/11, there has been an increased interest in developing a better understanding of the properties of fiber reinforced concrete under impact and blast loading and enhancing such resistance. This paper provides a historical perspective of our efforts aimed at understanding the impact resistance of fiber reinforced concrete and highlights some of the issues and challenges encountered. A synopsis of our current state of the art with respect to experimental and modeling attempts is presented. Finally, the paper attempts to chart our future course and identify areas where further research will be highly valuable.

Keywords: impact and blast resistance; fiber reinforcement; concrete

1. Introduction

Concrete in most instances is loaded at the strain rates approximated in our standardized tests. However, there are dynamic events (Comite Euro-International du Beton, 1988) in which the strain rates may significantly exceed those obtained in standardized tests such as in fast

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moving traffic ($\dot{\varepsilon} = 10^{-6} - 10^{-4}$ s^{-1}), gas explosions ($\dot{\varepsilon} = 5 \cdot 10^{-5} - 5 \cdot 10^{-4}$ s^{-1}), earthquakes ($\dot{\varepsilon} = 5 \cdot 10^{-3} - 5 \cdot 10^{-1}$ s^{-1}), pile driving ($\dot{\varepsilon} = 10^{-2} - 10^{0}$ s^{-1}), and aircraft landing ($\dot{\varepsilon} = 5 \cdot 10^{-2} - 2 \cdot 10^{0}$ s^{-1}). Inappropriately, though, the properties of materials used in the design of these structures are derived from standardized tests that are run at low quasi-static strain-rates (generally around 10^{-6} s^{-1}). Since concrete is known to be highly strain-rate sensitive in compression (Grote *et al*., 2001), tension (Malvar and Ross, 1998; Zielinski and Reinhardt, 1982) and flexure (Banthia *et al.*, 1989; Suaris and Shah, 1982; Gopalaratnam *et al.*, 1984), one cannot use its quasi-statically obtained properties to design structures that undergo high rates of loading; proper impact tests are needed. Loads during impact and blast are generally so large that the structure will often respond beyond its elastic state with cracking in concrete and plastic yielding in steel. An understanding of the complete constitutive response of the material including its postelastic stress transfer capability is therefore critical.

A large amount of energy is often imparted to the structure during an impact event. If the structure is not capable of absorbing the incoming energy, a failure during the event itself may ensue. Concrete, unfortunately, is a very brittle material with a poor energy absorption capacity. Any attempt at improving its energy absorption capacity by enhancing its postfracture stress-transfer capability will therefore be an effective way of improving its resistance to impact loads. Research in the last thirty years has indicated that the ideal way to enhance the postfracture stress transfer capability in concrete is by reinforcing it with fibers. Fibers bridge matrix cracks and undergo pull-out processes resulting in a significant enhancement in the fracture toughness of the material. While we understand very well the quasi-static properties of fiber reinforced concrete (FRC), its impact and blast properties largely remain poorly understood. For a better understanding of such properties, one needs to scrutinize and analyze the responses at the fiber-matrix interface level, at the level of micro-mechanical crack growth, and finally at the level of the engineering properties useful in design. It is only through such a multipronged approach that we can arrive at FRCs that can be classified as truly ‘high’ performance.

2. Test Techniques

A primary reason behind our lack of understanding of the impact resistance of FRC is the complete absence of a standardized test setup. Several techniques have been developed, including the *Drop Weight Test (*Banthia *et al*., 1989*)* in which a mass is raised to a predetermined height, and then allowed to drop directly on a concrete specimen. Similar in principle are the *Swinging Pendulum Machines* (Gokoz and Naaman, 1981; Suaris and Shah, 1982)—as in the conventional Charpy or Izod impact machines used by the metallurgists—where a swinging pendulum is allowed to strike a specimen in its path thereby transferring momentum and causing high stress rates. Other significant impact tests include the *Split Hopkinson Pressure Bar Test* (Zielinski and Reinhardt, 1982; Grote *et al*., 2001; Malvar and Ross, 1998) in which the specimen is sandwiched between two elastic bars and high stress rates are generated by propagating a pulse through one of the elastic bars using a drop weight or similar device.

In most modern impact test systems, sufficient instrumentation is provided such that along with loads and deformations, additional specimen responses such as accelerations, velocities, etc., are also measured; these are needed for a proper analysis of the data. One major issue that needs to be dealt with is that of inertial loading. With the exception of the Split Hopkinson Pressure Bar, all other impact tests result in high accelerations in the specimen that manifest as inertial forces in the system. In the case of ductile metals, one can ignore accelerations since failure occurs long after the specimen has accelerated and the inertial oscillations have died down. For a three-point bend specimen, the period of apparent specimen oscillation (τ) is given by Server (1978):

$$\tau = 3.36\frac{W}{S_0}\left(EBC_s\right)^{1/2}, \tag{1}$$

where W and B are specimen width and depth, respectively, C_s is the specimen compliance, S_0 is the speed of sound in the material, and E is its Young's modulus. It is recommended that only when the time to failure is at least three times greater than τ the inertial forces can be ignored. Unfortunately, in the case of brittle materials like concrete,

the failure is sudden and this requirement cannot be met; inertial forces must be accounted for to derive any meaningful information.

One commonly adopted technique is to carry out direct measurements of accelerations, and then use the principle of virtual work to derive expressions for generalized inertial loads. For a simply supported plate specimen impacted in the center, the generalized inertial load ($P_i(t)$) is given by Gupta *et al*. (2000):

$$P_i(t) = \frac{\rho \cdot h \cdot l^2}{4} \ddot{u}\left(x, \frac{l}{2}, t\right) \operatorname{cosec} \frac{\pi \cdot x}{l}, \tag{2}$$

where l is the width (also the length) of the plate, ρ is the mass density, h is the thickness of the plate, and $\ddot{u}(x, l/2, t)$ is the measured acceleration at any point $(x, l/2)$ on the plate at time t. Once the generalized inertial load is obtained, the plate can be modeled as a Single Degree of Freedom (SDOF) system and the generalized bending load can be obtained from the equation of dynamic equilibrium,

$$P_b(t) = P_t(t) - P_i(t), \tag{3}$$

Similar expressions have been developed for beam specimens (Banthia *et al*., 1987b) and other geometries (Bindiganavile and Banthia, 2003). Equally important in impact tests is to provide a proper energy balance. It has been shown that at the point of peak load only 20% of the hammer, energy is transmitted to the specimen and at failure this percentage rises only to about 50%; the rest of the energy

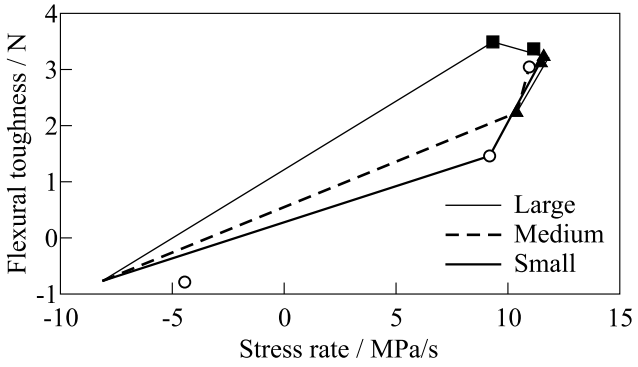


Figure 1. Influence of machine capacity on measured impact response of a given FRC material.

remains within the machine as elastic and vibrational energy. This has significant implications, and one cannot simply equate the hammer energy loss to that absorbed by the specimen.

Clearly, a number of these issues could be resolved if there existed a standardized test for concrete under impact loading. Data reported in the literature cannot be compared as they are obtained using different impact machines with different specimen support techniques, different energy loss mechanisms and different ways of generating high stress rates, all of which have a strong influence on the results. For example, drop weight machines that vary in size and capacity can lead to very different conclusions. In another study, Bindiganavile and Banthia (2001a) demonstrated (Figure 1) that very different flexural toughness values can be obtained for the same FRC materials by using machines of different capacities. Data from different labs, therefore, should only be compared for identical machine capacities.

3. Bond-Slip Mechanisms Under Impact

The interaction between a fiber and its surrounding matrix is the fundamental mechanism of FRC performance, and it is only at this level that its performance can be optimized. The routine method of understanding the interaction between a fiber and its surrounding matrix is by conducting a pull-out test on a bonded fiber. While significant research has been conducted to understand the quasi-static bond-slip response of various types of fibers, very little is known of bond-slip responses at high rates of loading, and there is a lack of general agreement in the literature. Gokoz and Naaman (1981) carried out bond-slip tests on aligned steel, glass and fibrillated polypropylene fibers at crack opening displacement (COD) rates of $4.23 \cdot 10^{-2}$ to 3,000 mm/s and reported negligible sensitivity for steel and glass fibers but an extreme sensitivity in the case of the fibrillated polypropylene fiber. Banthia and Trottier (1991) performed pull-out tests on aligned steel fibers at a COD rate of 1,500 mm/s and reported that the deformed steel fibers showed a greater sensitivity to rate than smooth fibers and produced smaller slips at higher rates of COD. This was in sharp contrast to the findings of Pacios *et al.* (1995) who showed that for straight steel fibers in an aligned group, the slips under impact were higher than those under quasi-static conditions, and the overall

sensitivity to rate was only minor. One major difference between the various studies cited above is how the inertial part of the applied load was dealt with. While a proper dynamic analysis was performed in (Banthia and Trottier, 1991), in (Gokoz and Naaman, 1981) and (Pacios *et al*., 1995), a rubber pad was introduced in the contact zone and inertial forces were ignored. As discussed above, it is now well recognized that inertial loading must be explicitly considered in all impact testing.

Some high performance polymeric macrofibers (also called polymeric structural fibers) have recently been developed (Trottier and Mahoney, 2001). While the quasi-static response of these high performance fibers is well understood, their response to impact and dynamic loads remains unknown. Preliminary testing (Bindiganavile and Banthia, 2001) has, however, uncovered an interesting trend (Figure 2): slip at peak load was seen to decrease as the rate of crack opening increased, but this decrease was far more pronounced in the case of polymeric macrofibers than for steel macrofibers. This pronounced bond stiffening in polymeric macrofibers is very encouraging and can be very useful in developing high performance composites for impact.

Clearly, significant further research is needed to fully understand the bond-slip mechanisms of various fibers under impact. In particular, the following variables need attention: fiber type and geometry, fiber inclination, fiber embedment length, fiber grouping, fiber coatings and chemical modification of fiber surfaces, temperature of the environment, concrete strength and the presence of a secondary fiber in the matrix.

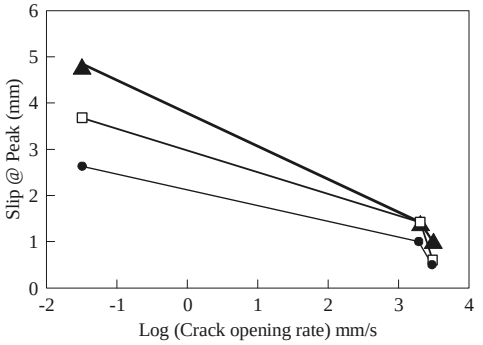


Figure 2. Bond stiffening in PP fiber under impact.

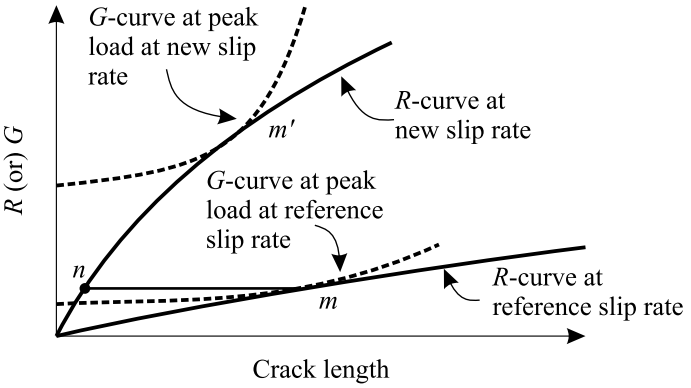


Figure 3. *R*-curves at different slip-rates. (Pacios *et al*., 1995.)

Limited efforts have been made to model the bond-slip process as a function of the strain rate. From the traditional R-curve approach in fracture mechanics, Pacios *et al.* (1995) assumed that the point of intersection of the *R*- and *G*-curves was a function of the slip-rate. That is (Figure 3), the ratio of the crack length at *m* to that at *n* depends upon the slip-rate as:

$$\frac{a^*}{a_c^*} = \exp\left(-AS_n^B\right). \tag{4}$$

Here, a_c^* and a^* are the crack lengths at points *m* and *n*, respectively; *A* and *B* are constants to be determined; and S_n is given by:

$$S_n = \log\left(\frac{s}{s^*}\right), \tag{5}$$

where *s* is the given slip-rate; and s^* is the reference slip-rate.

Peak pull-out load, *P*, is then obtained from:

$$P = \left\{\frac{4E_f \pi^2 r^3 \beta_n (a - a_0)^{d_n}}{\coth^2\left(w[L-a]\right)}\right\}^{1/2}, \tag{6}$$

where E_f is the modulus of elasticity of the fiber material; *a* is the debonded length at the fiber-matrix interface; *r* is the radius of the fiber; a_0 is the initial flaw size at the interface; *L* is the fiber embedded length; *w* is the parameter quantifying the shear stiffness of the interface;

$$d_n = \frac{1}{2} + \frac{\alpha_n - 1}{\alpha_n} - \left\{ \frac{1}{4} + \frac{\alpha_n - 1}{\alpha_n} - \left(\frac{\alpha_n - 1}{\alpha_n} \right)^2 \right\}^{1/2} ; \quad (7)$$

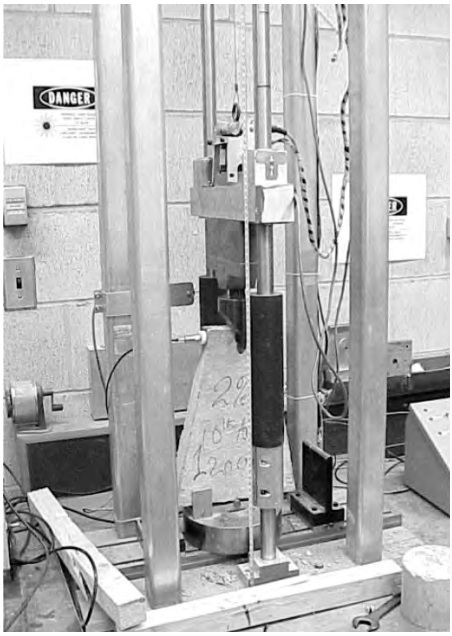
and α_n and β_n are the constants to be determined by using a reference specimen.

The existing models apply only to straight undeformed fibers and assume that the interface properties including fracture toughness are not affected by the applied strain rate. Need exists to develop sophisticated models that can apply to different fiber geometries and can explicitly include the strain-rate dependent properties of the interface.

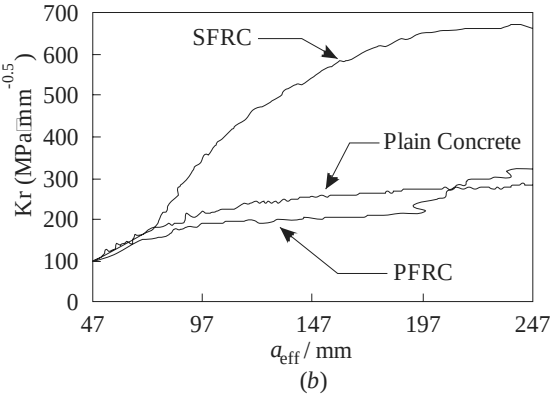
4. Dynamic Crack Growth Mechanisms

Analogous to the plastic zone in metals, at the tip of a critical crack in concrete, a microcracked 'process zone' develops and the crack essentially propagates in a stable manner before acquiring unstable conditions of failure. Solutions to the problem include the 'effective crack model' (Hillerborg *et al*., 1976) and the 'cohesive crack model' (Jeng and Shah, 1985), but these have not been applied under dynamic conditions.

In fiber reinforced concrete, in addition to crack closing pressures due to aggregate interlocking, fiber bridging occurs behind the tip of a propagating crack where fibers undergo bond-slip processes and provide additional closing pressures. The fracture processes in fiber reinforced cement composites are therefore even more complex and need advanced models to simulate them. Attempts have been made to model fracture in FRC using the cohesive crack model (Hillerborg, 1980) or by using the J-integral (Mindess *et al*., 1977). However, these are—strictly speaking—only crack initiation criteria and fail to define conditions for continued crack growth. To define both crack initiation and growth, there is now general agreement that a continuous curve of fracture conditions at the crack tip is needed, as in an *R*-curve (Mobasher *et al*., 1991). An *R*-curve is a much more suitable representation of fracture in FRC, as one can monitor variations in the stress intensity as the crack grows and produce a multiparameter fracture criterion. Further, an *R*-curve is particularly suited for dynamic loading, as one can incorporate dynamic stress intensity factors in the analysis



(*a*)



(*b*)

Figure 4. A dynamic crack growth test (*a*) and some dynamic *R*-curves (drop height = 1 m) (*b*).

and key—in their reduction as the crack speed approaches the Rayleigh wave velocity (Reinhardt, 1985). Unfortunately, the study of dynamic fracture mechanics of FRC is in its infancy, and significant doubt exists even on the exact velocity that cracks acquire during impact.

Mindess *et al.* (1985) observed crack velocities to be only one-tenth (~115 m/s) of the theoretically predicted Rayleigh wave velocity and found a further reduction to ~75 m/s in the presence of steel fibers. Similar observations were reported by others (Yon *et al.*, 1991) for plain concrete.

Some preliminary dynamic *R*-curves were recently obtained (Bindiganavile and Banthia, in press) using a contoured double cantilever beam specimen. The clarity and effectiveness of such a representation of dynamic fracture was clearly demonstrated (Figure 4). Unfortunately, however, much remains to be done. In particular, the following variables need to be studied: influence of loading rate, fiber volume fraction, fiber type and geometry, fiber coatings and fiber surface modifications, initial crack size, displacement rate, aggregate characteristics, temperature of the environment, strength of concrete matrix, and presence of a secondary fiber in the matrix.

5. Engineering Properties Under Impact

The micromechanical bond-slip tests and crack growth studies are a great tool to understand and optimize material characteristics. However, for designing structures, global responses of the materials, as determined by standardized tests for engineering properties, are required. Figure 5 shows a plot of some engineering properties under variable strain rates. Note that concrete is most rate sensitive under tensile load and least sensitive under compressive load. The sensitivity in flexure is in-between that under compressive and tensile modes of loading.

In spite of continued efforts in this area, our understanding of the engineering properties of concrete under impact loading remains severely limited, and contradictory data exist in the literature. For example, while Ross (1997) reported a reduced sensitivity to stress rate with an increase in the static strength of concrete, Bischoff and Perry (1995) reported otherwise. Also, while Banthia *et al.* (1989) reported an increase in the failure strains under impact Shah and John (1985) reported a reduction in the ultimate strains. There is also a 'knee' reported in strength (σ_f) vs. stress rate ($\dot{\sigma}$) plots, and the value of *n* in equation:

$$\sigma_f = k\dot{\sigma}^{1/(1+n)} \tag{8}$$

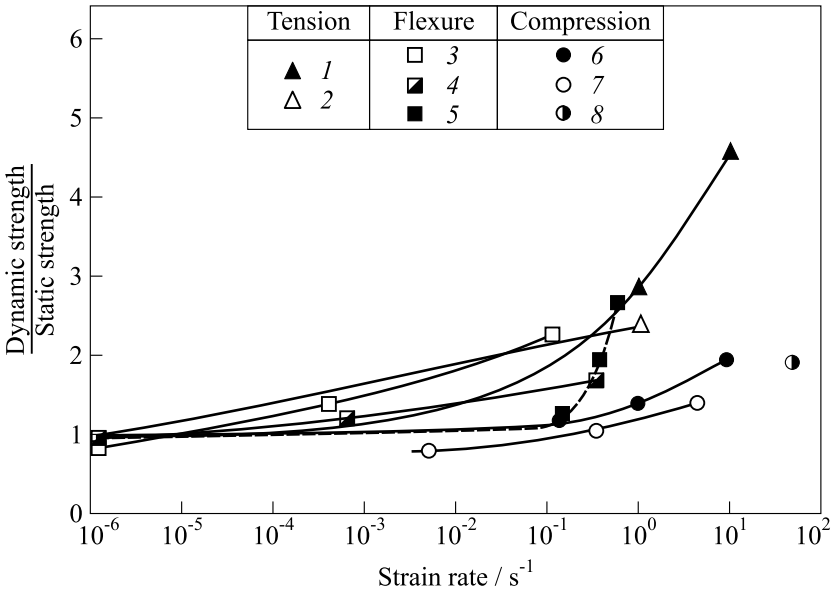


Figure 5. Strain-rate sensitivity of concrete in compression, tension and flexure: *1*—Birkimer, 1971; *2*—Zielinsky, 1982; *3*—Mindess and Nadeau, 1977; *4*—Suaris and Shah, 1982; *5*—Watstein, 1953; *6*—Evans, 1942; and *7*—Hughes *et al.*, 1972.

appears to decrease with stress rate. Origins of these anomalies are not known.

In the case of fiber reinforced concrete, while an improvement in impact properties is widely reported (Figure 6a, Banthia and Trottier, 1991), the exact magnitude of these improvements is uncertain. On a worrisome note, some FRC composites are reported (Banthia and Trottier, 1991) to fracture across cracks at high rates of loading and thus produce a brittle response at very high strain-rates.

As seen in Figure 6b, SFRC may depict inferior impact toughness than PFRC which is in agreement with Figure 2. Shear properties of FRC under impact have not been studied at all.

On the modeling side, only sporadic attempts have been made to predict the engineering properties of fiber reinforced concrete at high strain rates. Kaadi (1983) expressed the rate effects by the following expression:

$$\alpha\tau = (\alpha\tau)_{st}\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{st}}\right)^{0.05}, \qquad (9)$$

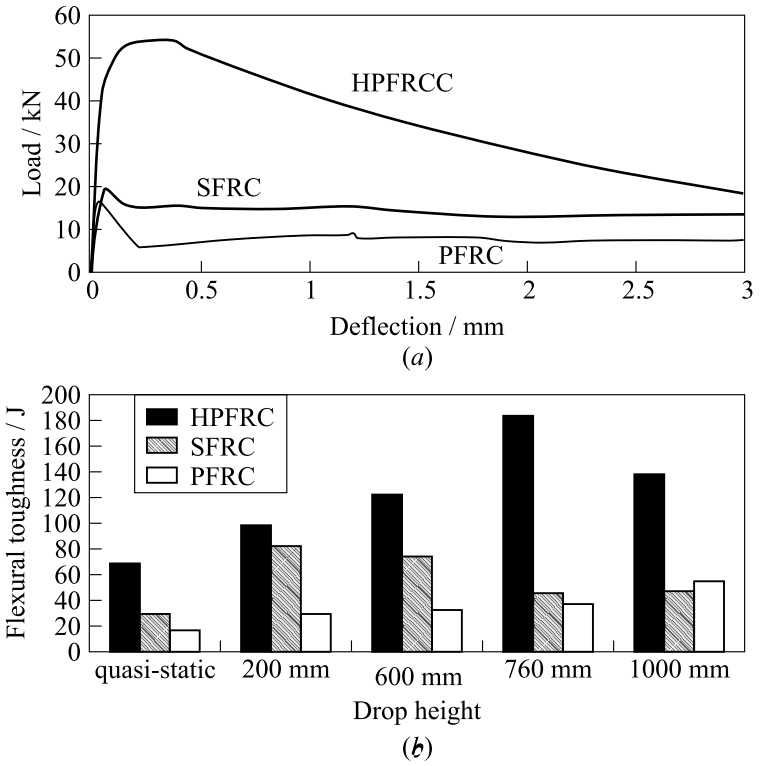


Figure 6. Load deflection curves (*a*) and toughness (*b*) of high performance FRC, normal steel fiber reinforced concrete (SFRC), and normal polypropylene fiber reinforced concrete (PFRC) under impact loading. Note a highly worrisome drop in toughness with an increase in rate of loading.

where α is the efficiency factor for discontinuous fibers and τ is the average interfacial bond strength. He then introduced this rate-dependent term into a model proposed by Visalvanich and Naaman (1983) to predict the rate dependent post-cracking stress-displacement relationship as follows:

$$\frac{\sigma}{\left[\alpha\tau(V_f l/\phi)\right]} = \left[\left(\frac{2\delta}{l}\right)-1\right]^2\left[1-a\left(\frac{2\delta}{l}\right)\right]. \qquad (10)$$

Here,

$$a = 1.15 \exp\left[1.78 \cdot 10^{-5}\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{\mathrm{st}}}\right)\right],$$

where $\dot{\varepsilon}_{\mathrm{st}}$ is the static strain rate equal to $1.57 \cdot 10^{-5} / \sigma$, σ is the post-cracking stress at a strain rate of $\dot{\varepsilon}$, and δ is the displacement corresponding to σ.

In a recent study, Bindiganavile and Banthia (2004) adopted a model proposed by Armelin and Banthia (1997) to predict the load-displacement response of a beam tested as per ASTM C1018 (Figure 7).

The compressive strain, $\varepsilon_{0,}$ at the top-most fiber of the specimen leads to an axial shortening, $\Delta_{0,}$ as shown. This, in turn, leads to stress, $\sigma_{c,}$ in the uncracked concrete. On the other hand, it results in fiber slippage, w_i, below the neutral axis and corresponding forces, f_1, as the fibers pull-out. Thus, the flexural load carried during the post-crack phase is obtained by satisfying the equilibrium of moments:

$$P = \frac{2M_e}{l}. \tag{11}$$

The equilibrating moment, M_e, may be calculated by summing the moments generated by concrete stresses and the individual moments generated by the N individual fibers bridging the crack below the neutral axis. It follows from Figure 7 that

$$\int_0^{c} \sigma_c (b dy) + \sum_{i=1}^{N} f_i = 0 \qquad \text{(equilibrating forces);} \tag{12}$$

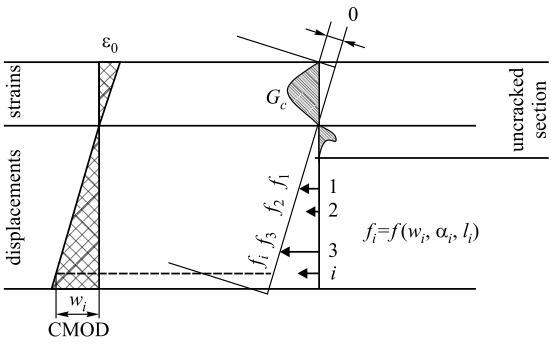


Figure 7. Schematic view of forces and stresses acting on the cracked section of an SFRC beam.

$$M_e = \int_0^{c'} \sigma_c (bdy) y + \sum_{i=1}^{N} (f_i y_i) \quad \text{(equilibrating moments);} \quad (13)$$

where b is the width of the beam, c' is the depth of the uncracked section, and y is the distance from the neutral axis.

In the model, the pull-out force in each fiber (f_i) is expressed as a function of the crack width, w_i, according to the average pull-out force vs. slip (or crack width) relationship obtained experimentally at the full embedment length, $l_e=l/2$. To enable this, single fibers must be pulled out from a concrete matrix at various inclinations with respect to the pull-out load. The bond-slip response is then represented using the Ramberg–Osgood formulation so that the force carried by each fiber may be expressed in terms of its orientation, α_i, and the slip, w_i, as follows:

$$f_i(\alpha_i, w_i) = E_p w_i \left\{ A + \frac{1 - A}{\left[1 + (Bw_i)^C\right]^{1/C}} \right\}, \quad (14)$$

where the constants A, B, C, and E_p are obtained for each orientation through the Ramberg–Osgood formulation. Recognizing that the average force in the fibers at a layer which is at a distance y from the neutral axis is averaged over the entire range of embedment and inclination that is possible, the value of f_i in Eqs. (12) and (13) may be computed as follows:

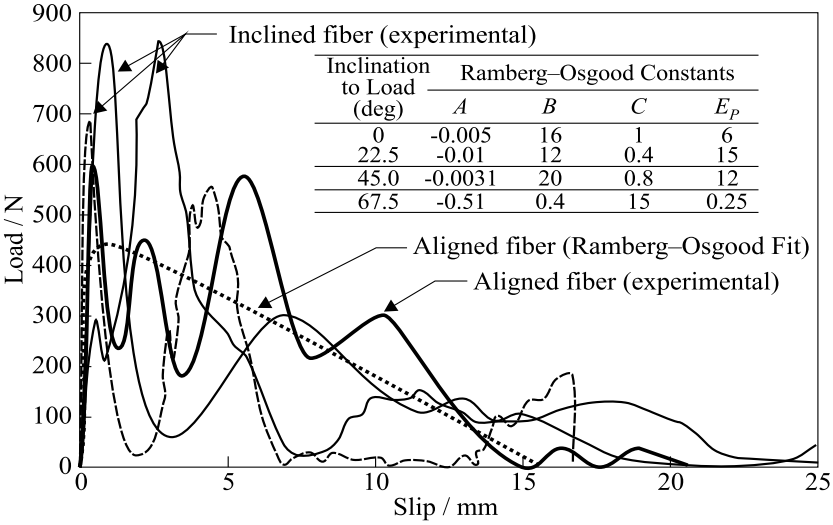
$$f_i = \frac{1}{2}\left\{ \left[\frac{f_0(w)}{2} + f_{22.5}(w) + f_{45}(w) + f_{67.5}(w) + \frac{f_{90}(w)}{2} \right] \frac{1}{4} + f_{\text{geometry}}(w) \right\} \quad (15)$$

or

$$f_i = \frac{1}{2}\left\{ \left[\frac{f_0(w)}{2} + f_{15}(w) + f_{30}(w) + f_{45}(w) + f_{60}(w) + f_{75}(w) + \frac{f_{90}(w)}{2} \right] \frac{1}{6} + f_{\text{geometry}}(w) \right\} \quad (16)$$

depending upon the number of different inclinations (4 or 6, respectively) tested.

Note that a change in the rate of fiber slip will result in a new pull-out load, f_i, in Eqs. (15) and (16). This rate dependence of f_i is reflected in a change in the constants for the Ramberg–Osgood fitted curve (Figure 8).



Inclination to Load (deg)	Ramberg–Osgood Constants			
	A	*B*	*C*	E_P
0	-0.005	16	1	6
22.5	-0.01	12	0.4	15
45.0	-0.0031	20	0.8	12
67.5	-0.51	0.4	15	0.25

Figure 8. Impact response of single steel fibers during pull-out (with the corresponding Ramberg–Osgood formulation for the aligned case).

Flattened end steel fibers were pulled out individually from a concrete matrix under dynamic loading at four orientations in increments of 22.5º. The resulting bond-slip responses is shown in Figure 8. Clearly, under impact, the bond-slip response is not a monotonic response unlike under quasi-static loading (Armelin and Banthia, 1997). Therefore, one may question the wisdom of choosing a Ramberg–Osgood formulation to represent the bond-slip response of these fibers under impact. Nonetheless, as a first approximation, in this study, the bond-slip curves were fitted using the Ramberg–Osgood expressions as shown in Figure 8 for an aligned fiber. The constants for the fitted curves are also shown.

Concrete is a stress-rate sensitive material as witnessed by the apparent increase in the flexural strength under impact (see Figure 5). Accordingly, in the model, the compressive strength has been adjusted to include this apparent increase.

The resulting model prediction is plotted together with the experimental flexural response under impact in Figure 9. Nevertheless, it is able to approximate the experimental response to a large degree. Notice that the model captures the flexural performance quite satisfactorily, as shown by the peak load and toughness measurements.

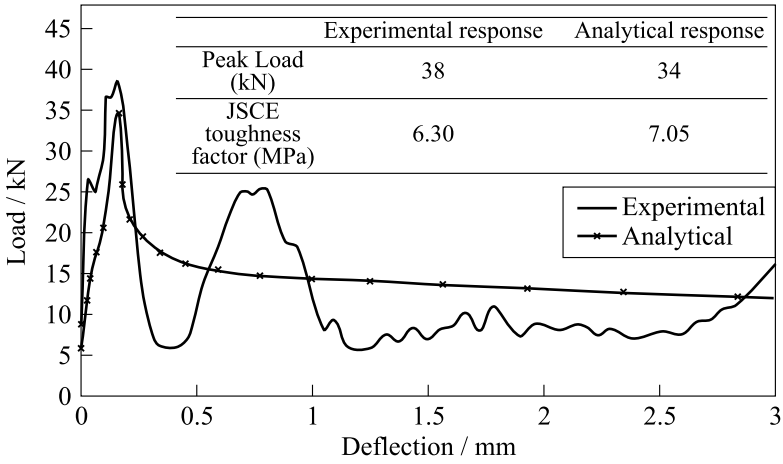


Figure 9. Impact response of an SFRC beam in flexure (notice the monotonic nature of the fitted curve in *Figure 8* and reproduced by the model for the flexural response above).

Plots in Figure 9 also indicate, and not surprisingly, that the analytical response is monotonic and it does not capture the true response. Clearly, one needs to bring in crack growth information into modeling effort in order to be able to accurately predict the true response of fiber reinforced concrete. Some such work is currently underway.

6. Concluding Remarks

The paper provides a brief description of our current understanding of the response of fiber reinforced concrete to impact and impulsive loads. While fiber reinforcement is the most effective way of enhancing concrete's resistance to impact and other dynamic loads, significant issues remain unresolved. There is a critical need to develop a standardized technique of testing FRC under impact loading. Without a standardized technique, progress will remain slow. At very high strain-rates, some fiber reinforced concrete materials may exhibit brittle responses due to changes in fiber failure modes. Crack growth processes and crack velocities under impact remain poorly understood. Finally, more sophisticated models are needed that can capture the responses of a variety of fiber reinforced concrete materials to a wide range of applied strain-rates.

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ENHANCING RESILIENCE OF URBAN STRUCTURES TO WITHSTAND FIRE HAZARD

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Abstract: A new class of materials referred to as high performance materials are being increasingly used in urban infrastructure projects. Many of these materials have poor or unknown fire characteristics and addressing the fire safety of these materials and their integration into structural systems are critical for ensuring the safety of the built infrastructure. In the paper, the different conditions and complexities associated with characterizing fire hazards in built-infrastructure is explained. The factors that have significant influence on fire performance of structural systems in built infrastructure are discussed. The fire resistance problems, and research needs, for emerging high performing materials are outlined. Design strategies for integrating fire safety design with structural design, through a performance based methodology is outlined. Construction guidelines for enhancing the fire performance of structures constructed with high performing materials are presented through case studies.

Keywords: Fire resistance; structural fire safety; built infrastructure; high performing materials; performance based design

1. Introduction

Fire represents one of the most severe environmental hazards to which buildings and built infrastructure is subjected, and thus fires account

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for significant personal, capital and production loss in most countries of the world each year. Therefore, the provision of appropriate fire safety measures for structural members is a major safety requirement in building design. However, traditionally, no specific fire resistance requirements are established for infrastructure projects such as bridges, tunnels etc. The main rationale for not considering fire resistance in the design is that, unlike buildings, there is no occupant safety involved in the case of fires in bridges, roads etc. However, there were a number of major fire-related accidents in tunnels and bridges in recent years. Therefore the traditional approach of not requiring fire resistance in an infrastructure project is often widely debated.

A state-of-the-art review reveals that the current prescriptive approaches for evaluating fire resistance in building have major draw-backs and do not provide rational and realistic fire safety assessment. Therefore, worldwide trends indicate a shift from these "prescriptive approaches" to "performance based" (PB) design of building systems, with a heavy emphasis on validated engineering practice and predicttions from computer simulations of "typical", in-service fire scenarios.

In addition, recent natural disasters (such as earthquakes, hurricanes etc.) and terrorism threats (blast and fire effects), have resulted in the need for repairing and strengthening older infrastructure that are rapidly losing their functionality, due to severe corrosion and other durability problems. For such repair and strengthening, a new class of materials referred to as high performance materials (HPM), (e.g., fibre-reinforced polymers (FRP), high strength concrete (HSC)), are being increasingly used. Many of these HPM have poor or unknown fire characteristics and addressing the fire safety of these materials and their integration into structural systems are critical for ensuring the safety of the built infrastructure.

In the paper, the different conditions and complexities associated with characterizing fire hazards in built infrastructure is explained. The factors that have significant influence on fire performance of built infrastructure (which includes buildings as well) are discussed. The fire resistance problems, for emerging high performing materials, mainly HSC and FRP, are outlined. Design strategies to integrate fire safety into overall structural design are suggested. The different steps associated with performance based fire safety design are presented and the importance of integrating fire resistance issues in infrastructure projects

into the overall design is highlighted. Guidelines that can be incurporated for enhancing the fire performance of high performance materials are presented through case studies.

2. Need for Structural Fire Safety

2.1. GENERAL

One of the major safety requirements in building design is the provision of appropriate fire resistance to structural members. The basis for this requirement can be attributed to the fact that, when other measures of containing the fire fail, structural integrity is the last line of defence. Fire resistance is the duration during which a structural member (system) exhibits resistance with respect to structural integrity, stability and temperature transmission. Typical fire resistance requirements for specific structural members are specified in building codes (ICC, 2003; NRCC, 2005). Fire resistance can play a crucial role in the performance of buildings and infrastructure in the event of fire incidents as seen in the collapse of the WTC twin towers and the damage to Euro-tunnel.

In contrast to buildings, there are no specific fire resistance requirements for infrastructure projects such as bridges, transit systems etc. The main reasoning for this is that in open spaces such as bridges there will be ample time for people to be evacuated from the fire zone in the event of fire. However, a number of recent fire-related accidents in bridges and tunnels, in North America and Europe, have opened a wide ranging debate on the fire resistance requirements for infrastructure projects.

Further, traditionally structural members in infrastructure projects were generally built with larger cross-sectional areas (required by structural design considerations alone), and with conventional materials, such as concrete, steel (protected) and masonry, which enhanced the fire resistance of structural systems. However, in modern infrastructure projects (and also in buildings), the use of HPM, together with sophisticated design techniques, based on non-linear methods of analysis aimed at optimizing the structural design, often lead to thin structural members, that might result in lower fire resistance characteristics. Hence, there is an urgent need for investigating the current

fire provision guidelines followed in infrastructure projects and for establishing the fire resistance of structural systems made of HPM.

2.2. FIRE INCIDENTS

The following recent incidents clearly illustrate the reasoning for fire safety concerns in buildings and built infrastructure such as tunnels and bridges:

On November 18, 1996, a serious fire on a shuttle train transporting trucks destroyed a section of the south tunnel of the railroad tunnel connecting England and France (Channel Tunnel Fire; Ulm *et al*., 1999). Nine trucks, ten train wagons and one locomotive burned for about 10 hours with temperatures up to 1,000°C. Eight people were injured and the cost due to damage to trains, track and tunnel, as well as disruption to services, was estimated to be as high as £50 M. The fire caused severe damage to the tunnel rings by thermal spalling over a length of a few hundred metres. The spalling in the 45 cm precast RC concrete rings reached an average depth of 10–20 cm. In some parts, thermal spalling of concrete destroyed the entire tunnel ring up to the chalk substratum. A post analysis of this fire incident indicated that the concrete employed in the Chunnel had typical features of HSC: a compressive strength of 80–100 MPa, and a low permeability (Channel Tunnel Fire). Based on the detailed investigation, major work had to be undertaken to repair the damage due to the spalling of the concrete.

The September 11th, terrorist incidents have caused colossal destruction and significant damage to a number of buildings in the World Trade Centre (WTC) vicinity in New York city. The massive impact from each of the aircraft resulted in severe structural damage at several floor levels in each tower. However, the towers withstood the massive impact, at least initially, despite this heavy but localized damage. The subsequent intense fires that followed, further weakened the already damaged structure resulting in the collapse of the floors, initiated at the floor with the worst fire conditions. In the twin towers the impact of aircraft mechanically damaged much of the spray-applied fire protection, originally present on the structural steel frame and lightweight bar joist trusses, to an extent that much of the steel in the immediate fire area was unprotected (FEMA, 2002; Kodur, 2003). The

Figure 1. Collapse of WTC 2 building as a result of aircraft impact and subsequent fires. (FEMA, 2002.)

intense fires on several floors, that followed the impact, weakened the bare steel. The impact load of the collapsing floors on the structure below started a progressive collapse and resulted in the complete collapse of the towers (FEMA, 2002) (Figure 1).

By the end of the day, four buildings completely collapsed, three buildings were severely damaged by fire leading to partial collapses, and seven buildings sustained significant damage, while numerous others suffered minor damage. Within 24 hours, about 2,830 people perished in the fires and subsequent collapse, and these included a large number of firefighters, police and rescue personnel. This incident turned out to be the worst ever building disaster on the U.S. soil. The fire issues, specially structural and material performance under high temperatures, played a major role in the collapse of the towers (FEMA,

2002; Kodur, 2003). In addition a number of other buildings, including WTC 7, suffered full or partial collapse, or significant damage as a result of fires. Thus, fire issues played a major part in the collapse of the twin towers and other WTC buildings.

Another example is the collapse of major high way bridge in Oakland, California, as a result of intense fire (Bulwa and Fimrite, 2007). On the morning of April 29th 2007 at about 3:45 AM a gasoline tanker carrying 8,600 gallons of gasoline crashed into a pylon on the interchange between I-80 and I-880.

The subsequent fire caused a 228 m section of the above interchange connecting I-80 to I-580 to collapse onto the road below. The fire is believed to have reached 1,100^{o}C, causing the steel to soften and allowing the interchange to collapse to the road below. Preliminary indications reveal that the means of failure was the overstressing of the connections during the fire and the collapse occurred in about 22 minutes after the start of the fire. As the fire progressed, the bolted connections in the collapsed girder began to weaken due to the heat; and were placed under increasing load from the weakening of the remainder of the bridge. The result is the “clean breaks” at the connections as seen in the Figure 2. While connections in steel structures represent a “weak link”, in situations such as these, they also provide a safety check. The connections failed before allowing the damage to propagate beyond the portion directly exposed to fire, thus minimizing damage, repair cost, and repair time.

Figure 2. Collapse of a highway bridge span as a result of fire. (Bulwa and Fimrite, 2007.)

2.3. HIGH PERFORMING MATERIALS

There have been significant advances and innovations in materials through research and development activities over the last three decades. In many cases the extensive laboratory research has resulted in modifications to the composition of conventional construction materials to improve performance considerations such as strength and durability. Examples of such high-performing materials used in civil infrastructure projects include high strength concrete (HSC), and fibre-reinforced polymers (FRP). While these modifications and alte-rations lead to better performance under ambient (room temperature) conditions, the same may not be true for situations such as fire exposure. In many cases, it has been shown that these modifications actually deteriorate the material and structural performance under fire conditions (Kodur, 2002). However, for repair and strengthening, these HPM offer a convenient and cost-effective means of rebuilding deteriorating infrastructure. Since many of these HPM have poor or unknown fire characteristics, addressing the fire safety of these materials and their integration into structural systems are critical for ensuring the fire safety in buildings and built infrastructure.

One example of HPM is HSC which is widely used in bridge girders and columns (as well as in high rise buildings) due to the improvements in structural performance, such as strength and durability, as compared to traditional NSC. Generally, NSC structural members exhibit good performance under fire situations. Studies show, however, that the performance of HSC is different from that of NSC and may not exhibit good performance in fire due to faster degradation of strength with temperatures and occurrence of spalling. The spalling of concrete under fire conditions is one of the major concerns due to the low porosity (low water-cement ratio) in HSC. The spalling of concrete (HSC) exposed to fire has been observed under laboratory and real fire conditions (Kodur, 2000). Spalling, which results in the rapid loss of concrete during a fire, exposes deeper layers of concrete to fire temperatures, thereby increasing the rate of transmission of heat to the inner layers of the member, including to the reinforcement. While many of the design standards for concrete structures have been updated with

detailed specifications for the structural design of HSC under normal (room temperature) conditions, there are no guidelines for the fire resistance design of HSC structural members (Kodur, 2000).

Another example of HPM is Fibre-Reinforced Polymers (FRP) which are used as internal (rebars) or external (wrapping and sheeting) reinforcement in new or existing (refurbishing) concrete structures because of their high strength, non-corrosive, non-magnetic and light weight properties. However, FRP due to combustible nature burn at early stages of fire exposure and also loose significant strength at relatively lower temperatures. Preliminary studies indicate that the performance of FRP under fire conditions is well below that of traditional materials. One of the main impediments to using FRP in buildings is the lack of knowledge about the fire resistance of FRP (Kodur *et al*., 2006a).

HPM are being developed to overcome shortcomings in traditional materials and are provided with superior properties under ambient temperatures. However, there is not much research, at present, to address fire-related issues of HPM in spite of serious problems with fire performance (Kodur, 2000; Kodur *et al*., 2006a). Addressing the fire-related issues is critical for the wider application of these HPM in buildings and other infrastructure projects where fire performance requirements are to be satisfied.

3. Factors Governing Fire Performance

All structural systems lose their strength and stiffness when exposed to temperatures commonly encountered in fire situations. To minimize such loss of strength and stiffness for a certain duration, buildings in the event of fire, rely on three basic fire defense mechanisms, namely sprinkler systems, active fire fighting and fire resistance (passive fire protection) to structural members, to overcome significant damage and collapse scenarios. Generally, the fire resistance performance of a structural system is a function of:

- Fire characteristics
- Material characteristics and
- Structural parameters

3.1. FIRE CHARACTERISTICS

Important aspects of fire behavior in the affected structural system involve the following issues:

- Burning behavior of materials (fuels), including mass loss and energy release rates
- Stages of fire development and
- Behavior of fully developed fires, including the role of ventilation, temperature development, and duration

The most important stage of fire that affects performance of a structural system is during the post-flashover (fully developed) phase of fire development. The intensity and duration of fire is a function of ventilation characteristics, fuel load, component size and other factors such as presence of sprinklers. These factors vary significantly with building type and component (size, lining material) characteristics. In case of infrastructure projects, the resulting fires in post-flashover can vary significantly depending on the fire load. As an example a loaded gasoline truck hitting a bridge can produce severe fires, while if it is an empty truck, then the resulting fire may not be severe.

Much of the current fire provisions contained in codes and standards are based on fire scenarios (ASTM, 2002), which represents typical building fires. These provisions may not be directly applicable to fires resulting in infrastructure projects such as bridges, and tunnels due to a wide range of differences in fire characteristics. These latter types of fires, often referred to as hydrocarbon fires, are much more severe (than building fires) and are characterized by fast heating rates or high fire intensities. These hydrocarbon fires, typically represented by Standard fire (ASTM, 1993), can pose a severe threat to the structural system. In Figure 3, the time-temperature curves from two standard tests and a typical building fire based on temperature measurements (DeCicco *et al.*, 1972) acquired in experiments involving office furnishing, is compared. Temperature development in the fires associated with infrastructure projects is likely to be closer to the ASTM E-1529 curve. Thus, the fire in infrastructure projects is likely to be much more intense than typical building fires and can reach very high temperatures within the first few minutes of fire exposure. Typical temperatures can reach beyond 1,000^{o}C within the first few minutes of fire occurrence and can go as high as 1,200^{o}C.

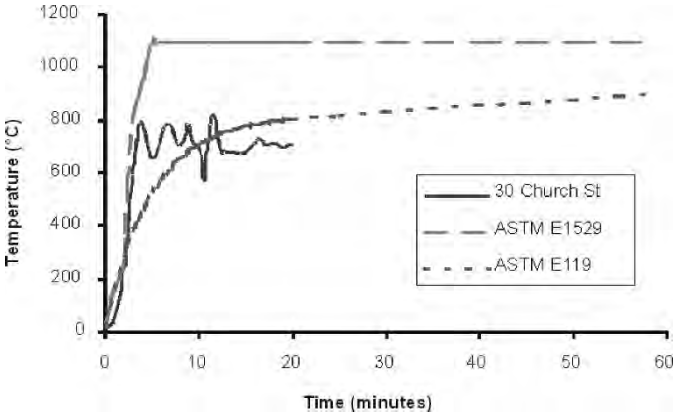

Figure 3. Time-temperature curves from two standard tests and temperature measurement in a typical building. (FEMA, 2002.)

Sprinkler systems can be very effective in protecting and minimizing the effects of fire. Automatic sprinkler systems are considered to be an effective and economical way to apply water promptly to suppress a fire. In the event of fire in a building, the temperature rise in the structural members located in the vicinity of sprinklers is limited. Therefore, the presence of sprinkler has to be included in evaluating fire temperature. Sprinkler systems, while common in buildings, may not be practical or feasible in all infrastructure projects.

3.2. MATERIAL PROPERTIES

The fire performance of structural members depends on the properties of the constituent materials (Kodur and Harmaty, 2002). Hence the knowledge of high temperature properties of constituent materials is critical for fire resistance assessment under performance-based codes. The temperature dependent properties that are important for establishing an understanding of the fire-response of structures include: thermal, mechanical and material specific properties (such as spalling) in concrete of constituent materials.

The thermal properties that influence the temperature rise and distribution in a structural member are thermal conductivity, specific heat, thermal expansion and mass loss. The mechanical properties that determine the fire performance of structural members are strength,

modulus of elasticity, and creep of the component materials at elevated temperatures. Creep, often referred to as creep strain, is defined as the time-dependent plastic deformation of the material. At normal stresses and ambient temperatures, the deformation due to creep is not significant. At higher stress levels and at elevated temperatures, however, the rate of deformation caused by creep can be substantial. Hence, the main factors that influence creep are the temperatures, the stress level, and their duration. In addition to thermal and mechanical properties, certain other properties, such as spalling in concrete and bond between concrete and rebar influence the fire performance of a structural member. In order to predict the spalling in HSC under fire conditions, additional properties such as porosity is required. These properties are unique to specific materials and are critical for predicting fire performance.

All the above properties vary as a function of temperature and have to be properly accounted for in tracing the fire response of structural members and for determining fire resistance. Figure illustrates the variation of strength with temperature for most commonly used construction materials.

The variation of many of the properties at high temperature is quite sensitive to small changes in materials composition (such as

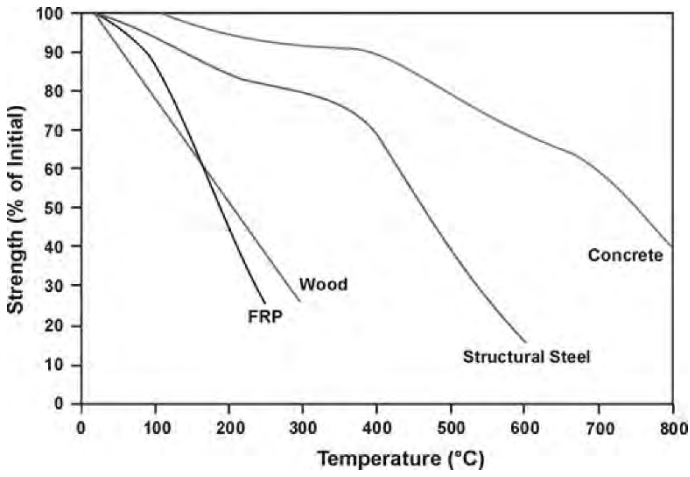

Figure 4. Approximate variation in strength of FRP, concrete, steel, and wood with increasing temperature. (Kodur and Baingo, 1999.)

chemical composition in steel or aggregate type in concrete) and environmental conditions (humidity and temperature rise). As an example the thermal properties are significantly influenced by the type of aggregate and composition of the concrete mix (Kodur and Harmathy, 2002; Lie, 1992).

The fire resistance of conventional materials, such as steel (with appropriate protection) and concrete (NSC), is superior to those of HPM. The required fire resistance for the conventional materials can be achieved through established fire protection measures (such as fire proofing in steel) and fire resistance assessment of these traditional materials can be made through simplified prescriptive approaches. However, due to inherent properties of HPM, the fire protection and assessment techniques used for traditional materials may not be applied to HPM (Kodur, 2002, 2005a; Kodur and Baingo 1999). This is illustrated through examples for two HPM, namely, HSC and FRP.

The fire performance of HSC is significantly different from that of NSC due to the occurrence of spalling and faster degradation of mechanical properties at elevated temperature (Kodur, 2000, 2005b).

Spalling results in the rapid loss of concrete during a fire exposing deeper layers of concrete to fire temperatures, thus, increasing the rate of transmission of heat to the reinforcement. The occurrence of spalling limits the use of critical temperature criterion for evaluating fire resistance of HSC structural members. Also, any fire protection techniques for NSC may not be adapted for achieving the required fire resistance ratings of HSC structural members, since spalling will alter the overall response of the system. Figure shows typical NSC and HSC columns after exposure to standard fire (Kodur and McGrath, 2003).

FRP unlike steel and concrete (NSC), as a material is often combustible and might even alter the fire characteristics. Further, there is wide variation in the composition of FRP (glass, carbon, aramid) and the orthotropic nature of these materials makes the fire resistance evaluation quite complex. Thus, simple fire resistance estimation techniques, such as the critical temperature concept, cannot be applied to FRP-reinforced structures (Kodur, 2002; Kodur and Baingo, 1999).

Also, commonly-used fire protection techniques for concrete and steel may not be adapted for achieving the required ratings of FRP structural members, since there are some major differences, such as combustibility and orthotropic property, associated with FRP as a material (Kodur and Baingo, 1999; Bisby *et al*., 2005).

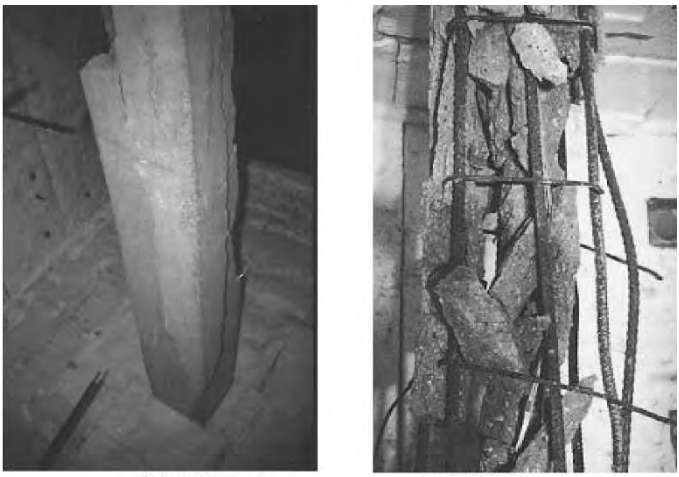

Figure 5. Spalling in NSC and HSC columns after fire resistance tests. (Kodur and McGrath, 2003.)

3.3. STRUCTURAL PARAMETERS

Several structural parameters influence the behavior of structural systems exposed to fire. The more significant factors are discussed here:

3.3.1. *Loading*

One of the major factors that influence the behavior of structural members exposed to fire is the applied load. A loss of structural integrity is expected when the applied loading is equal to the ultimate strength of the member. The fire resistance of the member increases if the applied load decreases. It should be noted that the load (stress) levels in infrastructure members might significantly be lower (than in building) during fire.

3.3.2. *Connections*

Connections play a significant role during fire exposure and determine the fire resistance. Beam-to-column connections in modern steel-framed structures may be either of bolted or welded, or a combination of these types. Most are designed to transmit shears from the beam to the column, although some connections are designed to provide flexural

restraint between the beam and column, as well, in which case they are termed “moment resisting.” When moment-resisting connections are not provided, diagonal bracing or shear walls must be provided for lateral stability. When fire induced sagging deformations occur in simple beam elements with shear connections, the end connections provide restraint against the induced rotations and develop end moments, reducing the mid-span moments in the beams. The moment resisted by connections reduces the effective load ratio to which the beams are subjected, thereby enhancing the fire resistance of the beams as long as the integrity of the connection is preserved. This beneficial effect is more pronounced in large multi-bay steel frames with simple connections.

3.3.3. *End Restraint*

The structural response of a member under fire conditions can be significantly enhanced by end restraints. For the same loading and fire conditions, a beam with a rotational restraint at its ends deflects less and survives longer than its simply supported counterpart. The addition of axial restraint to the end of the beam results in an initial increase in the deflections, due to the lack of axial expansion relief. With further heating, however, the rate of increase in deflection slows.

3.3.4. *Structural Interaction*

In contrast to an isolated member exposed to fire, the way in which a complete structural system (such as continuous beams, frames etc.) performs during a fire is influenced by the interaction of the connected structural members. This interaction is beneficial to the overall behavior of the complete structural system, because the collapse of some of the structural members may not necessarily endanger the stability of the overall structural system. In such cases, the remaining interacting members develop an alternative load path to bridge over the area of collapse. This is a current area of research and is not addressed by traditional standard fire-resistance tests.

3.3.5. *Other Factors*

A number of additional parameters have influence on fire performance of a structural system. Examples of such factors include composite action in steel-beam concrete slab assemblies and catenary action.

Catenary tensile membrane action can be developed by reinforced concrete floor slabs in a steel framed building whose members are designed and built to act compositely with the concrete slab (Wang and Kodur, 2000). This action occurs when the applied load on the slab is taken by the steel reinforcement, due to cracking of the entire depth of concrete cross section or heating of supporting steel members beyond the critical temperature. Tensile membrane action enhances the fire resistance of a complete framed building by providing an alternative load path to structural members that have lost their load bearing capacity.

3.3.6. *Temperature Distribution*

Depending on the protective insulation and general arrangement of members in a structure, structural members can be subjected to temperature distributions that vary along the length or over the cross section. Members subjected to temperature variation across their sections may perform better in fire than those with uniform temperature. This is due to the fact that sections with uniform temperatures will attain their load capacity at the same time. However, in some cases in members subjected to non-uniform temperature distribution, a thermally induced curvature will occur to add to the deflections due to applied loads and some parts will attain the load limit before the others. Non-uniform temperature distributions within structural members may be attained if the member is part of a wall or floor-ceiling assembly where the fire exposure is applied only to one side.

4. Design Strategies for Fire Hazard

Fire performance provisions for buildings are generally achieved through prescriptive provisions provided in building codes and standards. The current prescriptive approaches for evaluating fire resistance have major drawbacks and do not provide rational and realistic fire safety assessment, leading to a growing recognition that the perfor-mance based approach should be used. However, one of the main obstacles for moving towards performance based fire safety design is the limited availability of advanced numerical models and design tools. Further, the lack of a fire engineering framework, combined with a dearth of information on fire scenarios and high temperature material properties,

is hindering the application of rational approaches to fire safety. A review of the literature clearly illustrates that there are no methodologies and design tools for realistic assessment of structural systems response under fire conditions in infrastructure projects. However, the performance based approach that is currently used for buildings can be utilized for structural fire safety design in infrastructure projects.

4.1. FIRE — A DESIGN PARAMETER

As illustrated above, fire represents a significant hazard in built infrastructure and thus should be considered as a design parameter in the initial design stage, rather than treating it as a post construction fire protection strategy. While the performance objectives underlying fire design requirements in buildings are one of life safety, in infrastructure projects both life safety and property protection should be considered. Structural behavior is governed by the fire characteristics, response of the constituent materials, load response of components (columns, beams, and connections), and the complex interactions between the individual components that are part of the structural system. A fire, with the potential to damage or collapse structural system in an infrastructure, is a low-probability event in comparison with structural actions that are routinely considered in structural design (SEI, 2005), and many of the factors that determine safety under fire conditions are uncertain. Through performance based fire safety design approach, and through integration of fire resistance issues into the overall design, it is possible to achieve cost-effective and fire-safe design in built infrastructure. The following is one such strategy for achieving performance based fire safety design in built infrastructure.

4.2. ASSESSING HAZARD SCENARIOS

The hazard scenarios for each project should be assessed based on the probable occurrence of fire. The effect of probable fires on both life safety and property protection should be considered. The current approach of assessing fire hazard scenarios in buildings is heavily tilted on life safety. However, for infrastructure projects such an exercise should involve considerations to property protection and economic

losses in addition to life safety. Through these hazard scenarios, it is possible to estimate the vulnerability of structure and also impor-tance of the structural system. While, fire hazard may not be significant for many infrastructure projects, it may be crucial for certain projects (such as a major bridge connecting two islands). In such scenarios a detailed assessment should be made for establishing worst possible fire scenario expected to occur during the project life.

4.3. STRUCTURAL FIRE SAFETY DESIGN THROUGH ANALYSIS

In recent years, several mathematical models are developed to calculate fire resistance of structural systems in buildings. The introduction of high speed computers has stimulated the development of these methods and the use of them by practitioners. Such models can also be applied to evaluate the fire resistance of structural systems in infrastructure projects.

The flow chart in Figure , illustrates the general calculation procedure employed in such methods.

The fire resistance calculation is performed in three steps:

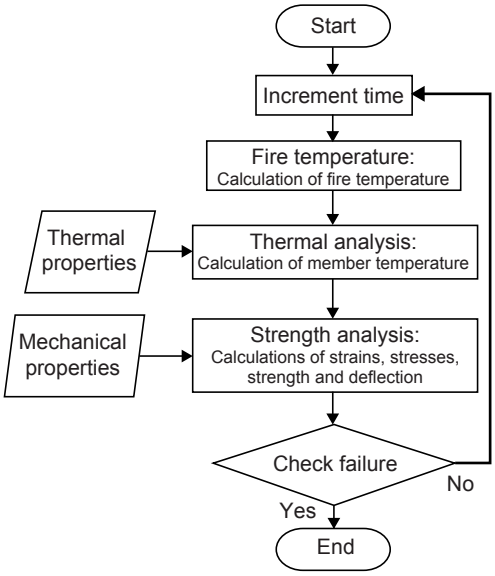

Figure 6. Flowchart for calculating the fire resistance of a structural system.

- Calculation of the fire temperature
- Calculation of the temperatures in the fire-exposed structural member and
- Calculation of the strength of the member during the exposure to fire, including an analysis of stress and strain distribution

4.3.1. *Fire Temperature*

The temperature in structural members and components is determined from a heat transfer analysis, which may range from one-dimensional analyses for simple structural components that are uniformly exposed to fire to a three-dimensional analysis for complex systems. Two-dimensional analyses often are sufficient for beams, bar joists or truss elements supporting floor or roof slabs. At present, in fire resistance calculations in buildings, the fire temperature course is assumed to follow the ASTM-E119 (ASTM, 2002) temperature-time relation. For non-building applications, such as infrastructure projects, other temperature-time relationships, such as ASTM-E1529 (ASTM, 1993), can be used to properly simulate the real fire exposure to the member or assembly. In addition certain design fire scenarios, as representative to infrastructure projects, should be considered. Typical design fire scenarios for buildings are given in SFPE Guide (SFPE, 2004).

4.3.2. *Structural Member Temperature*

The next step in the analysis is the calculation of the temperatures of the fire-exposed member.

These temperatures are calculated using a finite difference or finite element method. In these methods, the cross-section of the member is divided into a number of elemental regions, which may have various shapes such as squares, triangles or layers, depending on the geometry of the member (Lie, 1992). For each element or layer, a heat balance formulation is developed. By solving the heat balance equations for each element or layer, the temperature history of the member can be calculated.

The heat transfer analysis should consider changes in material properties (thermal properties), with increasing temperature, for all materials in the structural system. The boundary conditions should consider both radiation and convection heat transfer mechanisms, as appropriate. The presence of any fire resistive materials, in the form of

insulation or other protective measures, should be included in the heat transfer analysis. Two levels of structural analysis can be envisioned. When the focus is on the assessment of performance of individual members, or components subjected to a uniform heat flux and relatively uniform temperature distribution, simple methods can be used to develop cross sectional temperatures (Buchanan, 2001).

4.3.3. *Strength*

In the third step, a stress-strain analysis is conducted to determine the strength of the member during exposure to fire. This strength decreases with increasing temperature and the duration of fire exposure. The fire resistance is derived by determining the time at which the strength of the member becomes less than the load to which the member is subjected.

In order to calculate the strength of structural members, knowledge of the relevant mechanical properties at elevated temperatures is essential. Mechanical properties of various materials at elevated temperatures can be found in manuals and handbooks (Kodur and Harmathy, 2002; Lie, 1992). The methods and mathematical models to calculate the fire resistance of various concrete, steel, timber and composite members are also given in these manuals and handbooks. Decreases in stiffness and strength under fire conditions can be substantial. For example, at a temperature of 550ºC, the modulus of elasticity and yield strength of carbon steel are, approximately, one-half and two-thirds of their ambient (20ºC) values.

For undertaking detailed finite element analysis, the following factors are to be accounted for:

- Global structural analysis: The global structural analysis gives the fire performance of a complete structure rather than the performance of a single member. Further, it provides a far more realistic assessment and consequently helps in determining the best structural, economical and architectural solution.
- Realistic design loads: Since fire is an accidental event that rarely occurs, the analysis of the fire performance of a structure does not need to consider other rare events, such as the occurrence of maximum live load, simultaneously.
- Failure criteria: The predetermined failure criteria should include temperature, strength, deflection and rate of deflection and should

be checked at each time step. Failure is said to occur when any of the limiting states are reached. Four limit states are to be considered in evaluating failure namely: (i) heat transmission leading to unacceptable rise of temperature on the unexposed surface; (ii) breach of barrier due to cracking or loss of integrity; (iii) loss of load-bearing capacity; and (iv) excessive deflection (or deflection rate).

- Design fire scenarios: A real (design) fire, according to the specific features of the compartment, rather than a standard fire gives a more realistic assessment of the performance of the structure.
- Composite construction: Factors such as composite action (e.g., concrete-filling in HSS columns) and tensile membrane action arising from concrete slab has significant influence on the fire resistance of beams. By accounting for these factors higher fire resistance can be achieved.

5. Enhancing Fire Performance of HPM Structural Members

Similar to other structural members, the fire resistance of structural members made of HPM can be determined either by testing or calculation. In the last few years there has been some limited effort in developing fire resistance guidelines for HSC and FRP structural members for exposure to ASTM-E-119 (ASTM, 2002) fire conditions. The availability of such guidelines facilitates fire resistance requi-rements being integrated into conventional design of infrastructure projects. Such integration of fire resistance issues into the overall design will lead to rational and cost-effective design. The following case studies are presented to illustrate the application of such guide-lines in design situations involving HSC and FRP reinforced structural members.

5.1. HSC STRUCTURAL MEMBERS

High-strength concrete is widely used as columns and girders in buildings, bridges and other infrastructure projects. As illustrated before, fire performance is one of the major concerns due to the occurrence of spalling and decreased fire endurance. Recent research has shown that

it is possible to achieve good fire performance in HSC members through certain measures. Based on some of the recent studies, guidelines have been developed for the fire resistance design of HSC structural members (Kodur, 2005b; Kodur and McGrath, 2006). These guidelines can be integrated in to the normal design process of infrastructure projects.

The fire endurance and the extent of spalling in HSC columns is influenced by the tie configuration adopted for the column (Kodur and McGrath, 2003; Kodur *et al*., 2006b). In the case of reinforced concrete columns installation of bent ties (when the ties are bent at 135^{o} into the concrete core) helps to minimize spalling and enhances fire endurance (Figure 7).

Further provision of cross ties also improves fire resistance. These measures can be integrated into conventional design at an early stage to mitigate spalling and enhance fire endurance of HSC columns.

The second solution which can be effectively integrated into HSC members (columns, decks, girders and slabs) is through the addition of polypropylene fibres to the concrete mix (Bilodeau *et al*., 2004; Kodur *et al*., 2003). The addition of fibers, about 0.1–0.15% by volume helps to minimize thermally induced spalling and enhance fire resistance of HSC members. The polypropylene fibers melt at a relatively low temperature of 170°C, and create "channels" for the pore (steam) pressure in concrete to escape, and thus prevent the small "explosions" that cause the spalling of the concrete. The effect of polypropylene fibers is very beneficial in minimizing spalling in HSC members under hydrocarbon fire exposures (Bilodeau *et al*., 2004; Kodur *et al*., 2003). This is illustrated in Figure, which shows two HSC concrete blocks two hours of hydrocarbon fire (Bilodeau *et al*., 2004).

(a) Conventional Tie Configuration (b) Modified Tie Configuration

Figure 7. Conventional and modified tie configuration for reinforced concrete column.

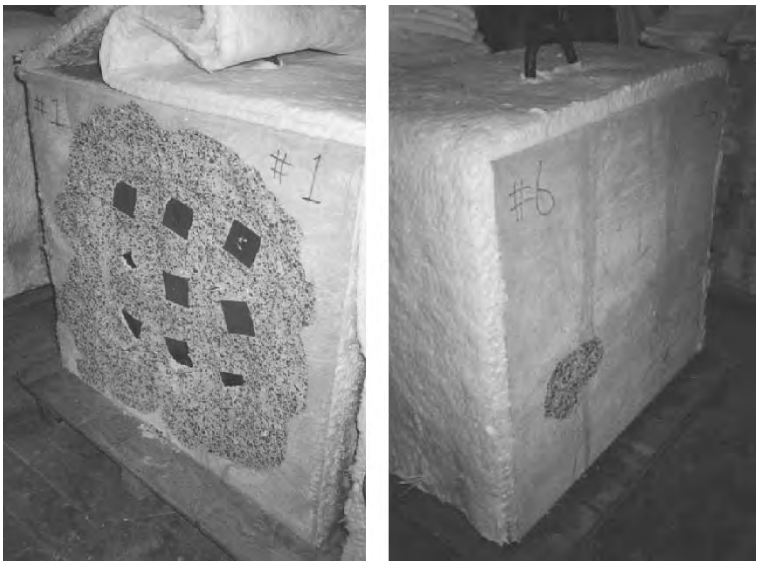

Figure 8. View of HSC Blocks, without (*a*) and with (*b*) fibres, after 2 hour hydrocarbon fire tests. (Bilodeau *et al*., 2004.)

The two HSC blocks were made of normal weight aggregate: one with polypropylene fibers and the other without any fibers. It can be seen from the figure that there is a significant reduction in spalling in the block made from HSC with polypropylene fibers.

5.2. CONCRETE STRUCTURES STRENGTHENED/RETROFITTED WITH FRP

Fibre reinforced polymers are high-performance materials that offer a number of advantages and hence widely used in strengthening and retrofitting of structural systems of buildings and infrastructure projects. In recent years, a significant research effort has been undertaken to quantify the behaviour of the FRP-strengthened RC systems and to quantify the factors influencing their performance at room temperature. Guidelines have been developed for the design of these systems and these guidelines are now available in building codes and design documents. However, there is limited research on fire perfor-mance of FRP systems, and hence few rational guidelines currently exist for fire

resistance design of FRP-reinforced structural systems. Based on the limited studies undertaken in recent years, the following are preliminary guidelines for enhancing the fire performance of FRP systems for concrete (Bisby *et al*., 2005; Kodur *et al*., 2007):

- Unlike conventional RC members, FRP-strengthened concrete members require suitable fire protection insulation, in most cases, to achieve the required fire performance under increased service loads. The performance of protected (fire insulated) FRP-strengthened concrete systems at high temperatures can be similar to, or better than, that of conventional RC members.
- Figure 8 shows FRP strengthened, and insulated, RC column before and after exposure in a standard fire resistance test.
- To protect against sudden and complete loss of effectiveness of FRP wraps during fire, the strengthened (with FRP wrap/plate) service load on the RC structural member should not exceed the design strength of the unstrengthened (preexisting) RC structural member. This requirement is similar to a strengthening limit requirement currently suggested by ACI Committee 440, and also provides a measure of protection against poor installation practices or vandalism.
- FRP-strengthened RC members (columns, slabs, beams) protected with suitable fire protection system are capable of achieving required levels of fire resistance (fie resistance of 2 hours or more) under standard fire exposure scenario and under full service loads.
- All insulated FRP-strengthened concrete members provide satisfactory fire endurances, even though the glass transition temperature of the FRP polymer matrix exceeds relatively earlier in the fire exposure. Thus, reaching of matrix T_g of an FRP during fire does not indicate failure of the FRP-strengthened concrete system.

5.3. CONCRETE SLABS REINFORCED WITH FRP REBARS

The use of FRP reinforcement in concrete structures, as an alternative to traditional steel reinforcement, has increased significantly in recent years due to their extremely high corrosion resistance. This makes them suitable for use in structures subjected to severe environmental

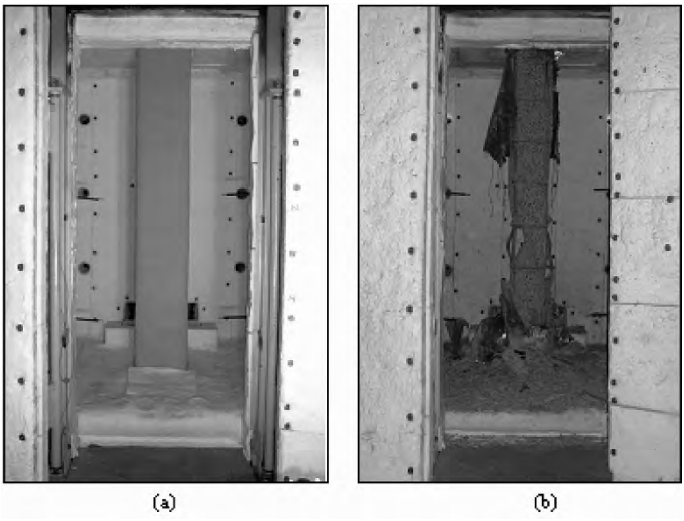

Figure 9. Square FRP-wrapped and insulated column (a) immediately before testing and (b) after failure.

exposure. Applications for FRP reinforcing bars as internal reinforcement in concrete structural members (slabs and beams) include parking garages, multi-storey buildings and industrial structures. In many of these applications provision of appropriate fire resistance is one of the major design requirements. At present, there is very little information available on the performance of FRP-reinforced structural members in fires.

The recent edition of CSA standard "Design and Construction of Building components with Fibre-Reinforced Polymers" (CSA, 2002) provides detailed guidelines for evaluating the fire endurance of structural members reinforced with FRP bars. In this standard there are a series of design charts that provide guidance on the required cover to FRP reinforcement for a particular overall slab thickness, critical temperature of reinforcement, aggregate type, and fire resistance rating (Bisby and Kodur, 2007).

Two examples of design charts for estimating fire resistance of FRP-reinforced concrete slabs are shown in Figure 10 and Figure 11.

These graphs can be used for evaluating fire endurance of concrete slabs provided the slab properties and critical temperatures of reinforcing bars are known. The critical temperature for GFRP (Glass-FRP) and CFRP (Carbon-FRP) reinforcing bars is 325°C and 250°C respectively while for steel rebars it is 593°C. As an illustration, a 180 mm thick carbonate aggregate concrete slab reinforced with GFRP rebars and with a concrete cover of about 40 mm will have about 65 minutes fire endurance. For a similar slab with CFRP rebars the fire endurance is 45 minutes. If the slab were reinforced with steel rebars the fire endurance would be about 240 minutes.

The design charts can also be used to estimate the required concrete cover to the reinforcement for a desired fire resistance rating and a known reinforcement critical temperature. For instance, for a 120 mm thick FRP-reinforced concrete slab (of carbonate aggregate

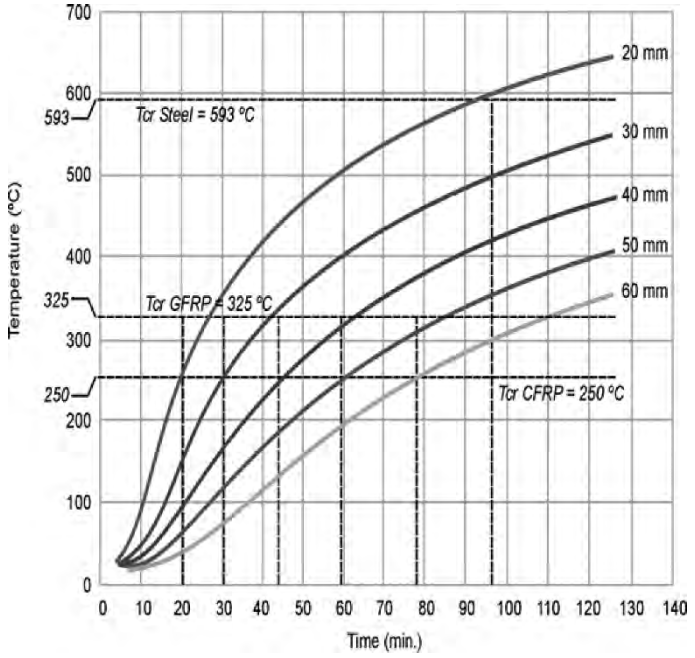

Figure 10. Design chart for 180 mm thick carbonate aggregate concrete slab. (CSA, 2002.)

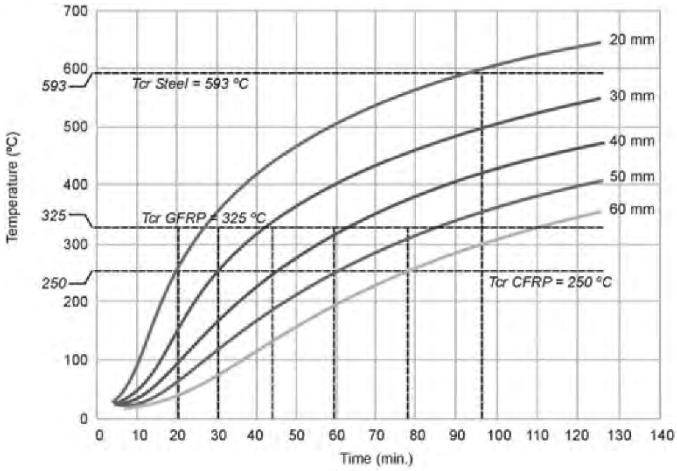

Figure 11. Design chart for 120 mm thick carbonate aggregate concrete slab. (CSA, 2002.)

type) with a desired 1-hour fire resistance rating, a CFRP bar or grid with a critical temperature of 250°C would require a concrete cover of about 50 mm, while for a GFRP bar or grid with a critical temperature of 325°C, the required concrete cover would be about 40 mm (see Figure 11).

For a conventional steel reinforcement slab, a concrete cover of about 20 mm will provide a fire resistance of approximately 90 minutes. Thus the availability of such design charts will facilitate the integration of the fire resistance design into overall structural design of deck slabs.

6. Concluding Remarks

Based on the information presented in this paper, the following conclusions can be drawn:

1. Fire represents a significant hazard in built infrastructure and should be considered as a design parameter in structural design.

2. Many of the high performing materials have poor fire resistance properties and appropriate fire-safe solutions should be incorporated in to design when such materials are used in infrastructure projects.
3. Cost effective and fire-safe design of structural systems in built infrastructure can be achieved through performance based fire safety design. The framework available for performance based fire safety design in buildings can be utilized for the fire safety design in infrastructure projects.
4. There is a need for further research to develop innovative solutions for overcoming fire hazard in buildings and built infrastructure.

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CONCRETE STRUCTURES UNDER BLAST LOADING
DYNAMIC RESPONSE, DAMAGE, AND RESIDUAL STRENGTH

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Abstract: The resilience of a city confronted with a terrorist bomb attack is the background of the paper. The resilience strongly depends on vital infrastructure and the physical protection of people. To judge the vulnerability, to assess the resilience, and identify effective countermeasures, risk assessment tools are needed. The paper starts with a general problem analysis and the approach that was defined by TNO to contribute to develop safety assessment tools. An important and basic element in the safety chain is the passive protection layer, while in safety assessment, the residual functionality of the vital infrastructure is of major importance. Specific knowledge is needed to design effective passive protection and enable explosion damage prediction. Dedicated research has been defined in The Netherlands and addressed in this paper.

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1. Introduction

According to a recent United Nations report, in 2008, most of the world population will live in cities. Especially the last two centuries, the urbanization process accelerated. In the early 19th century, only 3% lived in urban areas. One hundred years later, it was about 15%, while now, in the early 21st century, the 50% will be exceeded.

Cities are attractive for most people. Early mankind built the city Babylon with a mighty tower to stay together (Figure 1). The extensive urbanization of last century in the (western) world was possible due to the effective agricultural techniques and to large-scale industrialization. Also, in the poor countries, people move to cities, but it is a “get away” hoping for a better life.

People living and working together in a city, in a limited area, bring along strong demands on city planning. The shortage of land across The Netherlands and in most Western Europe countries has led to the development of design and construction techniques that make intensive and multiple use of the limited space possible. Combining functions in the same infrastructure has the major drawback of increasing the vulnerability of the city to accidents and disasters.

Figure 1. Multiple use of space in the old city of Babylon according to Pieter Brueghel.

Besides the accidental hazards, nowadays, we are also confronted with the extreme and unpredictable threat of terrorism. How vulnerable are we? And what measures can be taken to control the threat and limit the consequences?

This paper starts in Section 2 with a general problem description of risk assessment of a city. The city is a complex system, consisting of numerous elements with interrelated functions. To protect such a system, the Layer of Protection principle can be applied. Layers of active protection are combined with a "solid" layer of inherent, passive protection which is the physical resistance to the threat.

The focus in this paper is on the most likely terrorist threat scenario, i.e., a bomb attack. Crucial in the risk assessment and the design of the protection layers is the possibility to quantify the damage and consequences of the explosion. Section 2 gives a general description of the problem, the needs for technical knowledge to enable this quantification and the approach that was defined in The Netherlands to meet the requirements. Special research projects were defined to gain specific knowledge. Section 3 reports on the ongoing project on the prediction of blast damage to reinforced concrete structures. The paper ends with some concluding remarks.

2. Risk Assessment for a City

2.1. THE CITY SYSTEM

In order to quantify risks, first, the city has to be defined and described in characteristic and representative elements, functions, relations, and dependencies. The city-system can be described in numerous ways because the city consists of (i) people forming a community, (ii) a society, people living and working together, (iii) an economy, and (iv) an infrastructure formed by buildings, roads, bridges, and numerous networks for, e.g., water, energy, and data. A full, general description of the city covering all the functionalities and representative elements is hardly feasible and not very efficient for risk assessment. It is suggested to define the city-system tailored to the kind of risk that is considered. For example, when the safety of people is considered in case of a bomb attack in a shopping mall, the damage to the infrastructure is relevant because of the secondary explosion effects, the evacuation routes, and

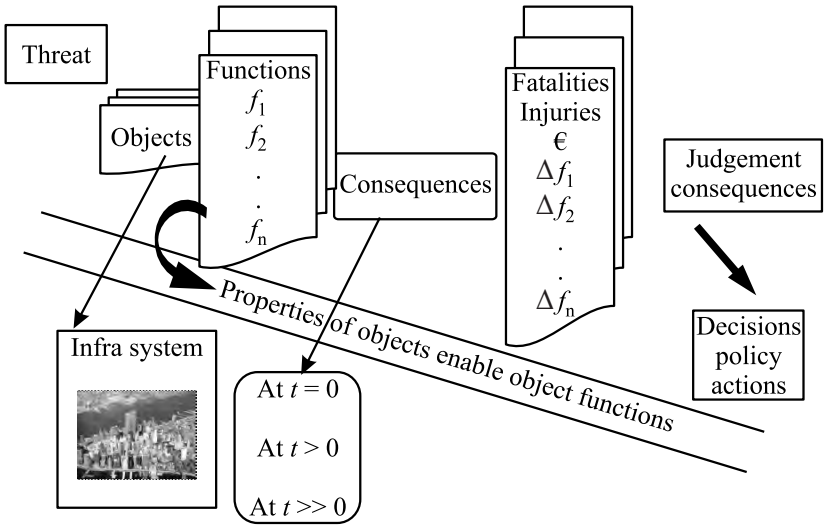


Figure 2. Step sequence in risk assessment.

the accessibility to first responders. But the economical loss due to structural damage and the rupture of, e.g., a main energy supply chain has not to be quantified. However, if the economical risk has to be quantified, elements of the system that must be considered are logistics, production units, banks, ICT, etc. When these are damaged, loss of specific functionalities occurs and the system may be disordered for a long time. If the overall risk is relevant, a method has to be selected (or defined) to deal with the "sum" of the different kind of risks.

In spite of the differences for all risk assessments, the general scheme is formed by the steps depicted in Figure 2. In words: first, the threat scenarios are defined. For a bomb attack location, charge weight and time are scenario parameters. The infrastructure objects that are affected by the blast load have to be defined and characterized. Resistance to explosive loading, the kind of functions and where these are located in the object(s) and also the population are parameters of the system description. Interdependencies between functions have to be specified to cover domino effects.

The threat, the bomb attack will cause damage, injuries, loss of functionality immediately at time zero. These consequences may develop and expand in time. Judgement of the consequences is the next

step followed by decisions and counteractions with reference to all steps in the safety-chain (pro-action, prevention, preparation, represssion, and follow-up care).

Vital to the quantitative risk assessment is the damage prediction to the objects, the infrastructure. The properties of the objects enable the functions. Consequently, damage to the objects is directly related to the loss of functionality. Based on this observation, it was proposed by the authors to focus the Dutch R&D programme on two aspects; (i) the ability to quantify the explosion damage in terms of damage zones, volumes, and damage levels and (ii) the possibility to couple the damage volumes and damage levels to the loss in functionality in time.

2.2. LAYERS OF PROTECTION

A common method to realise safety for an industrial plant is to apply layers of protection. The goal with instituted layers of protection is to come as close to a "safe failure" of the system as possible. The same counts for the safety of the urban infrastructure. Layers of protection can be defined in the "safety-chain." Starting, for example, from intelligence, road blocks, observation of the objects, resistance of the building, fire extinguishers, evacuation routes, and emergency training. Designing a protection system one should be aware that the safety and security measures have to be in respect to the freedom of the individuals. The accepted reduction in freedom depends on the risk awareness and is implicitly not constant. Another fact is that layers of so-called active protection might fail. Therefore, the layer of passive protection, the inherent safety, is vital. It provides the last protection when the other layers fail (Figure 3).

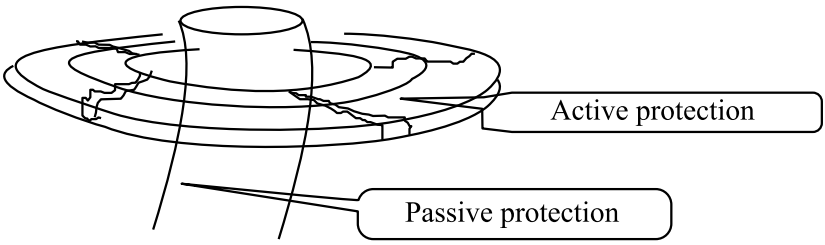


Figure 3. Passive layer of protection is vital to the protection system.

For the explosion threat, the passive protection layer is formed by the structural resistance to the explosive loading. Explosive charge weight, distance, the dynamic response of the structural system and material up to failure are the important parameters. Knowledge needed to quantify the explosion damage and designing explosive resistant structures is not common in (civil) engineering practice. For example, (i) nonlinear design is needed for the extreme dynamic loading conditions, (ii) safety factors are well established for normal loading conditions, but in nonlinear designs, the safety factors and failure limit states are not evident, and (iii) knowledge on the dynamic material behavior up to failure is scarce.

It has been concluded that (i) damage assessment of explosively loaded structures is a key issue in safety assessment, (ii) passive protection is vital to the protection system, and (iii) the required knowledge for damage assessment and protective design is only partly available. To address these issues, a dedicated research programme on blast damage prediction has been defined in The Netherlands.

2.3. BLAST DAMAGE PREDICTION RESEARCH PROGRAMME

There are no methods readily available to predict quantitatively the damage level in buildings and civil engineering infrastructures as a consequence of large explosion loads. Particularly, for construction materials like concrete and masonry materials, tools and knowledge to predict damage are still limited. The main reason is that knowledge development has been focused on design. This means a focus on general load conditions during service life with hardly any damage, and the maximum resistance (ultimate bearing capacity).

A research programme was defined and TNO was tasked to evaluate different potential methods to quantify damage due to blast loading. Theory, engineering methods, numerical simulations, and experimental facilities are applied and combined in order to identify the feasibilities and limitations of each and the advantages and disadvantages at a quantitative level. The evaluation is performed using basic bearing structural elements, e.g., columns and slabs, as bench-marks. The first results on the damage prediction research are given in Section 3. But first, the envisaged approach will be sketched.

2.3.1. *Outline Damage Assessment Methodology*

When analysing structures, the traditional approach is to subdivide the structure in basic elements, which are characterized by material, size, and boundary conditions, to analyse these elements separately and to combine the results at a later stage. This limits the number of relevant structures to a set of basic structural elements.

The basic structural elements are slabs, columns, and beams. The boundary conditions vary from fully clamped, simply supported, to free ends. The bearing capacity and functionality of the basic elements are determined by their capacity to carry normal forces, bending moments, and shear forces. Critical to the overall structure are the resistance to normal forces and bending moments (Figure 4). Considering external explosions, the slabs and columns are loaded perpendicular to their span, a load they are usually not designed for. The potential damage zones are near the supports and at mid-span. Damage at the supports leads to a potential loss in bearing capacity of the connected floors and beams. This also counts for a permanent mid-span deflection combined with the normal forces. Therefore, the actions to quantify the residual bearing capacity of structural elements (column and slab) are:

- Determine the load-deformation relation for equally distributed static load normal to the span directions
- Quantify the dynamic response of the element for different levels of blast load (P_1,...,P_n)

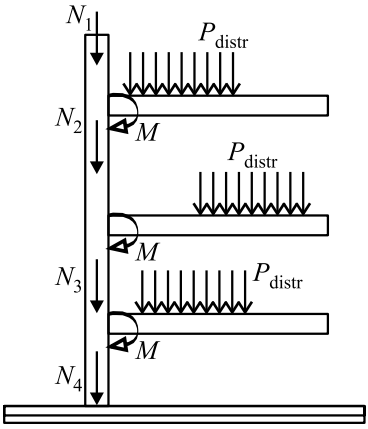


Figure 4. Loading scheme of column.

- Quantify the damage at the supports and mid-span due to the different blast levels
- Quantify the permanent deflection at mid-span
- Quantify the permanent displacement of the supports
- Quantify the load-deformation relation for equally distributed static load at the quantified damage levels (D_1,...,D_n)
- Quantify the reduction in strength and stiffness for the support regions and
- Quantify the residual bearing capacity of the column/slab for normal and bending loads

The envisaged methodology to quantify the residual bearing capacity after blast loading consists of these steps. Critical is the step to predict the damage due to the blast loading. The initial and residual resistance of a structural element is represented in the load-deformation relation, the so-called resistance curve. This relation is the central theme in the three methods mentioned (engineering, FE, and experiments).

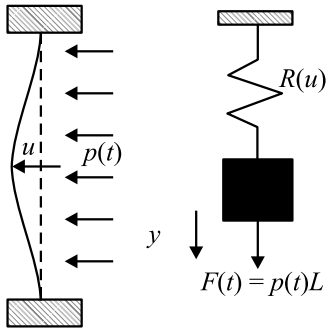
3. Damage Prediction Research

The dynamic response and failure of a structural element can be described in a simple manner by means of a Single Degree of Freedom (SDOF) concept, which is briefly addressed in Section 3.1. To determine the dynamic response, the induced damage and failure mode, as well as the resistance of RC structures, a number of square plates have been tested by means of a blast simulator. In these tests, displacements and accelerations are monitored (Section 3.2). The experiments are modeled in Section 3.3.2 using the explicit FE code LS-DYNA, and the K&C concrete material model. The resistance function of the slabs was selected to compare the computational results with the experiments and the SDOF approach. A modification to the common SDOF approach is introduced. This equivalent SDOF system has the advantage of being equivalent energetically to the entire structural response. The FE model is used in Section 3.3.3 to predict the residual strength of a plate loaded in its plane direction after blast loading.

3.1. ENGINEERING RESPONSE MODEL

In engineering practice, the response of a structure is often studied by means of a SDOF system (Figure 5). A number of assumptions are made. There is one dominant deformation mode, from the initial elastic regime up to final failure. Rate effects on material properties are neglected or taken as a constant for the entire response process. The SDOF approach and so the balance Eq. (1) in Figure 5, is widely discussed in textbooks (Biggs, 1964). The K_{lm} factor is derived from the quivalence of kinetic and deformation energy of the continuum and SDOF system, while the resistance to deformation is represented in the function $R(u)$. The selected degree of freedom is, e.g., for a symmetric, clamped slab the mid-span deflection, u. To incorporate damage development, and resistance reduction, the damage parameter $\omega(u)$ is introduced.

In the SDOF, the static resistance function is applied, assuming that the dominant response and failure mechanisms under the dynamic loading and static loading are similar. To judge the applicability of this approach for damage assessment, FE-calculations have been performed and a test procedure has been developed to determine this function of RC-slabs under dynamic loading (Sections 3.3 and 3.2, respectively). The deformation capacity under blast loads is obtained and the direct comparison with the (theoretical) static resistance function tells us about the validity of the simplifications on the single dominant deformation mode and the constant material properties for the entire response process.



$$K_{lm}M_l\ddot{u} + R(u) = F(t) \qquad (1)$$

$$R_{eff} = \frac{R}{1 - \varpi} = R_{eff}(u_e, \alpha_i) \qquad (2)$$

$$\varpi = \varpi(|u_p|) \qquad (3)$$

Figure 5. Continuum system and equivalent SDOF model with damage resistance.

3.2. REFERENCE TESTS

The resistance of a concrete element to dynamic loading strongly depends on the dynamic response of the structure and the material rate effects. At TNO-DSS, a test procedure was developed to derive the dynamic resistance from experiments (van Doormaal and Weerheijm, 1996). This method is applied to a batch of square reinforced concrete plates of dimensions 1,600 × 1,600 × 100 mm tested by a blast simulator, at different pressure levels. The plates are simply supported at four sides. To allow edge rotations, rubber strips are placed between the plates and the blast simulator. Displacements, accelerations, and pressure history are recorded using sensors placed at characteristic points on each plate (Figure 6), which will allow determining the dynamic plate resistance, as discussed in Section 3.3.2.

Measurements revealed that the supports were not fixed. Hence, the plates underwent two motions: (i) bending, due to the difference in displacement between the boundaries and the center of the plate, which causes damage; and (ii) a rigid body translation, due to the supports compliance, which does not cause damage.

Figure 7 shows the relative displacements at some gauge locations.

The effective pressure, which is the total pressure minus the rigid body inertia, is shown in Figure 8. The measurements provided all the required input for the reconstruction of the dynamic response up to failure, and the reference data for the numerical analysis.

(*a*) (*b*)

Figure 6. Blast simulator at TNO DSS (*a*), and extensive cracking after a blast load of 160 kPa peak pressure (*b*).

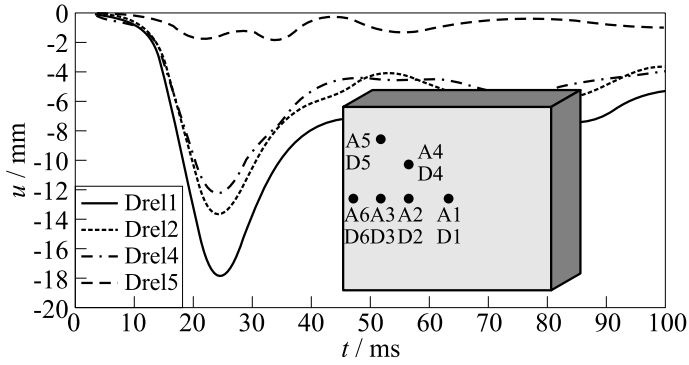


Figure 7. Measured relative displacements (Di–D6) and gauge points.

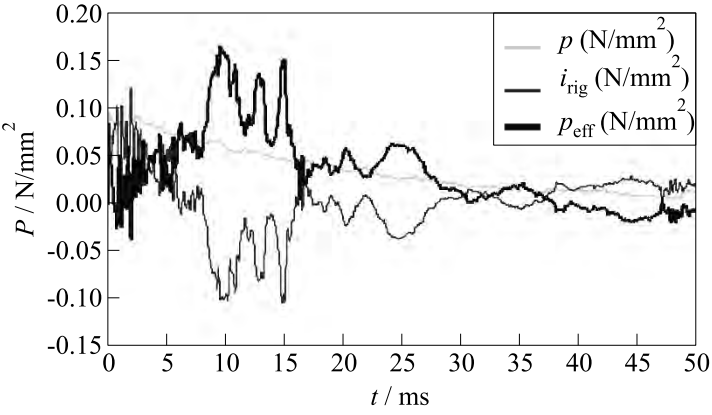
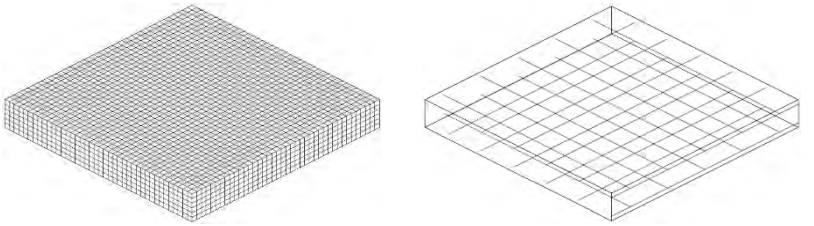


Figure 8. External pressure (p), rigid body inertia (i_{rig}) and effective pressure (p_{eff}).

3.3. THE FE-CALCULATIONS

3.3.1. *The FE-Model*

The dynamic response of the concrete plates is simulated with the explicit FE code LS-DYNA (Hallquist, 2005). Simply supported boundary conditions are assumed at all four sides. Because of the symmetry, only one quarter of the plate is simulated. Unless otherwise specified, the blast is simulated as a uniform pressure with a linear decay and constant blast duration of 45 ms, so that the impulse is similar to what is measured in the experiments.



(*a*) (*b*)

Figure 9. Half mesh with double solid elements (concrete and elastic) (*a*) and rebars (*b*).

Concrete is modeled using continuum eight-node brick elements (six layers of elements in slab thickness) and material type K&C (Figure 9a) The K&C model (Malvar *et al.*, 1997) is originally based on the pseudo-tensor model (MAT_16) and features a three surface plasticity formulation, softening, shear dilatancy, a nonassociative flow rule, and strain rate effect. The reinforcement bars are modeled using Hughes–Liu beam elements (Figure 9b) and a von-Mises elastoplastic material with kinematic hardening, strain rate effects, and a strain failure criterion. Perfect bonding (no slippage) is assumed between concrete and rebars.

3.3.2. *Resistance in the Equivalent SDOF System*

Section 3.1 summarized the SDOF approach. The major assumption is the single mode response. Under impulsive loading initially also the higher response modes are activated. Consequently, the choice of the mid-span deflection of the first mode will introduce errors. To account for all vibration modes, an alternative, "equivalent SDOF" is introduced, (Figure 10) based on the average displacement $\overline{Y}$, which is determined in an FE calculation.

The resistance R is computed indirectly from the balance equation:

$$\overline{R} = F_{ext} - K_{lm} M_{tot} \ddot{\overline{Y}} \tag{1}$$

with the known definition of the variables, except that here $\ddot{\overline{Y}}$ represents the average plate acceleration ($M_{tot}\ddot{\overline{Y}}$ is thus the total inertia) and $\overline{K}_{lm}$ factor enforces the conservation of energy between the structure, with all its vibration modes, and the SDOF model:

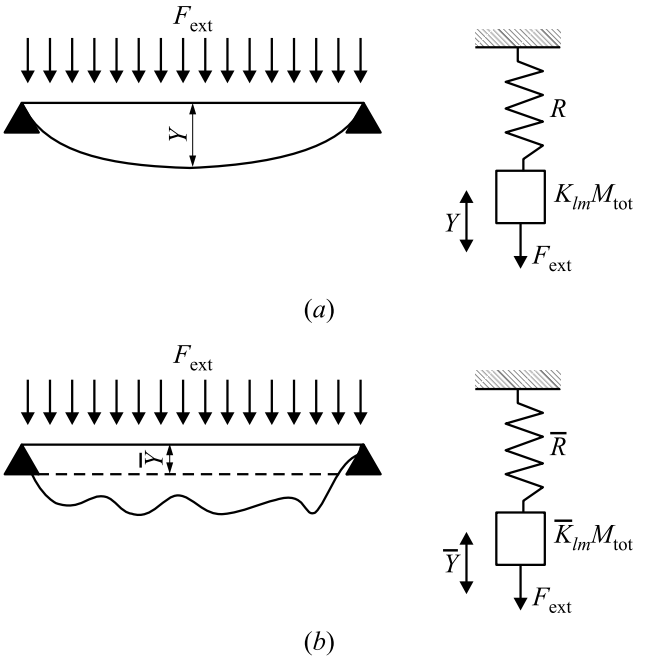


Figure 10. Single vibration mode (*a*) and infinite vibration mode (*b*) system, continuum and equivalent discrete systems.

$$\overline{K}_{lm}(t) = \frac{\int_{\Omega} \frac{1}{2} \rho \dot{y}^2 d\Omega}{\frac{1}{2} M_{tot} \dot{\overline{Y}}^2}. \tag{2}$$

The response was calculated with the FE-code taking all eigenmodes into account and the properties of the equivalent SDOF were determined. The $\overline{K}_{lm} = \overline{K}_{lm}(t)$ is a function of time, but it oscillates around a constant value (Figure 11), which is the constant to be used in the equivalent SDOF model. The $K_{lm}(t)$ based on the mid-span deflection exhibits a much stronger fluctuation (see Figure 11) and should preferably not be used for impulsively loaded structures.

The resistance-displacement curve is a property of the structure, and therefore, should be the same regardless of the magnitude of the loading, provided that the same mechanisms are mobilized and strain rate effects are neglected (see SDOF assumptions, Section 3.1). To

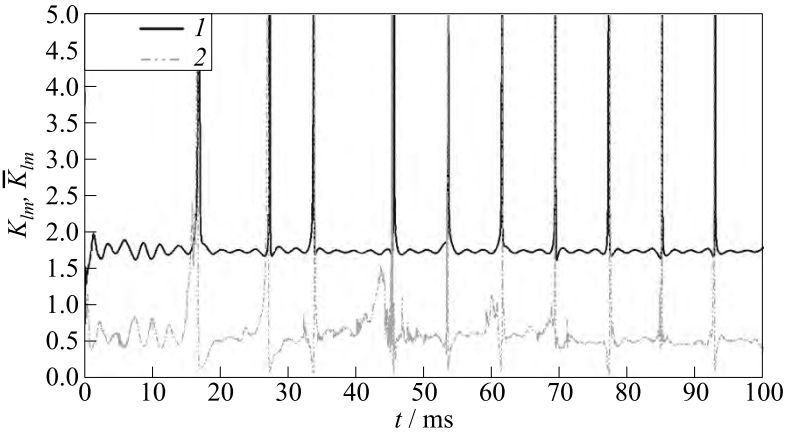


Figure 11. K_{lm} versus time for a concrete plate loaded by a blast pressure with a peak load of 100 kPa.

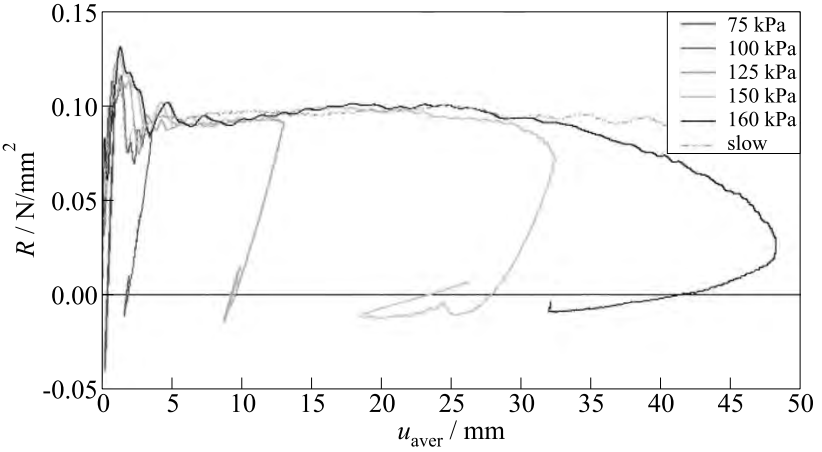


Figure 12. Resistance-average displacement curves of reinforced concrete plate for different blast pressures (75–160 kPa).

elucidate this point, the resistance-displacement curve has been computed for an idealized linearly decaying blast pressure (duration 5 ms) and different peak pressures (75–160 kPa). After a short elastic phase, the plate evolves from hardening to softening (see Figure 12). As expected, all curves lie on top of each other. The apparent decrease in stiffness during unloading with increase in blast pressure is due to the increase in plasticity/damage. The strain-rate effect is noticed in the higher resistance with increasing pressure (i.e., increasing strain rate) (Figure 13).

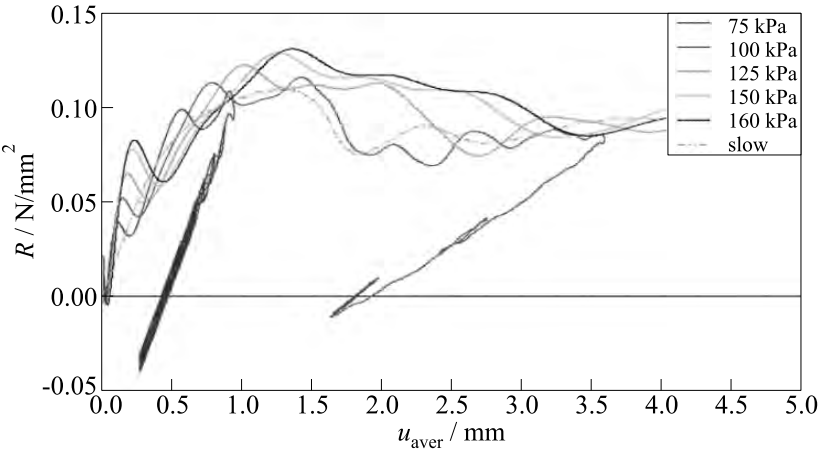


Figure 13. Close-up of resistance-average displacement.

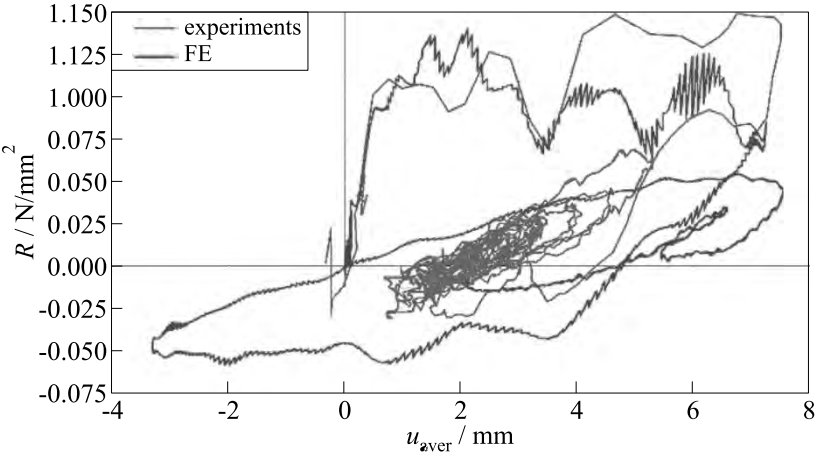


Figure 14. Experimental and simulated resistance-relative average displacement curves of reinforced concrete plate under an explosion with a peak blast pressure of 96 kPa.

The computational and experimental resistances have been compared in Figure 14. The FE analysis has been performed using the effective pressure (see Section 3.2) as input load and fixed (i.e., simply supported nonmoving) boundary conditions. Experiments and simulations show similar patterns proving the LS-DYNA capabilities. Evidently, there are still quantitative differences, especially in the unloading phase, see also (Iacono *et al.*, 2006; Mediavilla *et al.*, 2007a, b). In the applied material model, the rate effect on strength is covered explicitly

using experimental data. The same rate dependency is assumed to be valid for the fracture energy (G_f). Recent research (Weerheijm and van Doormaal, 2007; Vegt and Weerheijm, 2007) proved that this assumeption is not valid and results in too high G_f-values and under prediction of the damage. Concerning the material modeling, attention has to be paid to the concrete softening and the bond between reinforcement and concrete under dynamic loading.

It can be observed that the resistance curve obtained for a plate with moving boundaries differs from that with fixed boundaries, as presented in Figure 12. Apparently, different response and damage mechanisms are mobilized by the different load types. In the blast loaded, fixed boundary case, the slab is loaded by a shock load with a linear decay, while in the moving boundary case, the load (effective) resembles more a sine function. The dynamic effects will be less pronounced in the latter case.

3.3.3. *FE Damage Prediction*

The predicted damage fields corresponding to the three blast loads (75, 100 and 150 kPa) are shown in Figure 15. These resemble the crack pattern observed in the experiments. It should be noted that in the experiments, the yield line pattern, formed by the zone of macrocracks, is narrow banded compared to the damage zones in the computations.

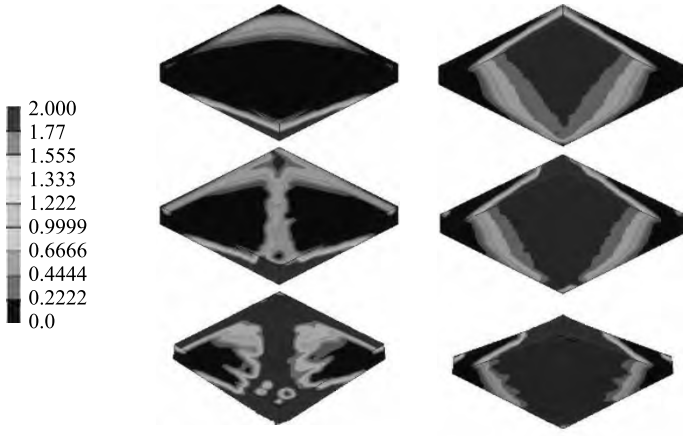


Figure 15. Damage fields at t = 100 ms, for three different blast pressures 75 kPa, 100 kPa, and 150 kPa; (*a*) the loaded side and (*b*) the unloaded side.

3.3.4. *Residual Load Carrying Capacity*

From safety point of view, it is crucial to determine the plate residual strength after the blast explosion. To examine and illustrate the possibilities to use the LS-Dyna code for the static and dynamic response, the following case was explored (Figure 16). The same plate as described in the previous sections is loaded by a load $q_0 = 2$ N/mm^2 in its plane direction. The plate is exposed to a blast pressure perpendicular to its plane, with duration 45 ms and a linear decay. Different pressure amplitudes are considered. After the blast, the plate vibrates freely. Once the free vibrations have damped out by means of numerical damping, the vertical load is slowly increased until failure occurs.

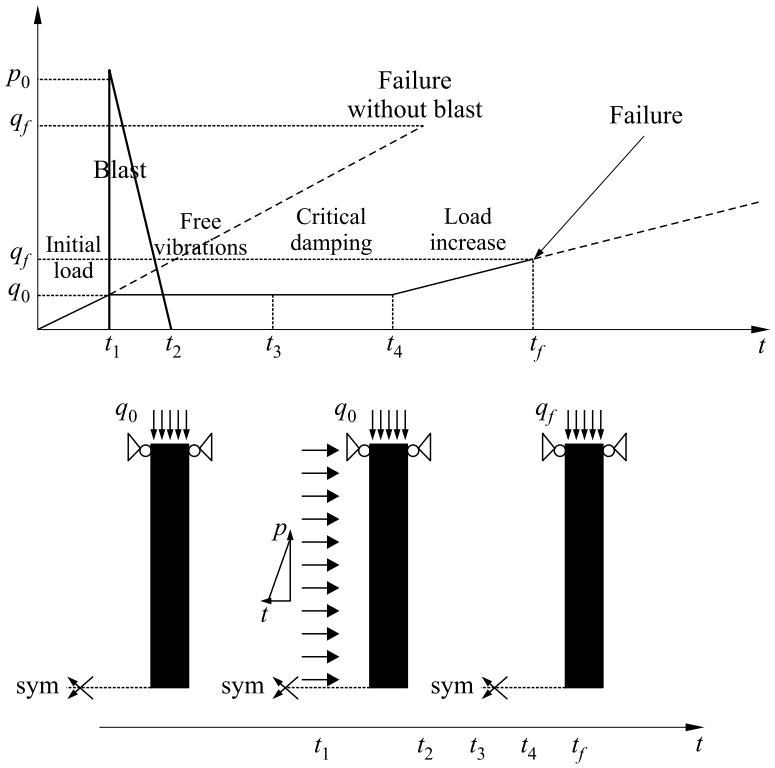


Figure 16. Loading history to failure strength for a plate under static in-plane load and dynamic bending load.

The reduction in failure strength due to an explosion can be computed using a relative failure strength index r_s

$$r_s = \frac{q_f}{q_f^o} \tag{3}$$

which is the ratio between the static failure load after blast q_f, and the failure load without blast q^o_f.

Another important parameter is the global damage index D_g:

$$D_g = 1 - \frac{q_f}{q_f^o} = \frac{\Delta q_f}{q_f^o} \tag{4}$$

The parameters r_s and D_g range between 0 and 1. Parameter $r_s = 1$ ($D_g = 0$) represents an undamaged state, i.e. the explosive loading was below the elastic limit. On the contrary, $r_s = 0$ ($D_g = 1$) indicates a total strength reduction, caused by a large explosion. A state in between corresponds to a certain amount of damage and a strength reduction.

Figure 17 shows the relation between D_g and the applied blast load (normalized with the concrete compressive strength). The relation exhibits first a linear damage increase with load amplitude. After a certain threshold load level (100 kPa in the example) the damage increases exponentially. The failure load q_f is determined by the failure time t_f at which a large increase in the average acceleration is detected. Obviously, the onset of failure occurs sooner for higher blast pressures.

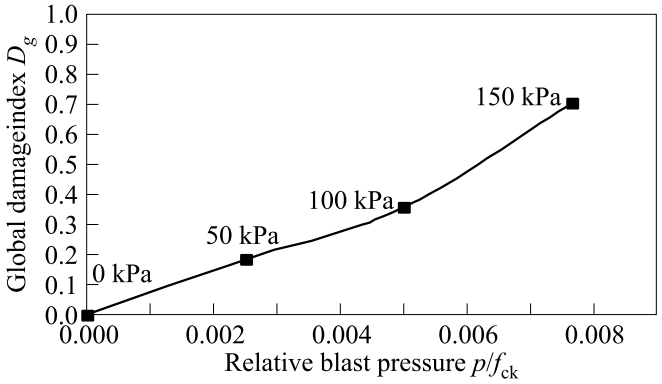


Figure 17. The global damage index.

The results presented show that prediction of the damage due to blast is feasible with LS-Dyna. The overall response (resistance function) corresponds with the experiments.

Also, the residual bearing capacity can be predicted numerically using LS-Dyna, although the code is designed for dynamics. Note that experimental validation of the static residual strength has not been performed yet and is recommended.

3.4. CONCLUSIONS OF THE DAMAGE PREDICTION RESEARCH

The combined experimental and computational research reported in this chapter on the capability of engineering approaches and advanced FE-codes to predict damage and residual bearing capacity of RC-slabs, is a part of a larger programme on the damage assessment of large, multistorey buildings (see Section 2). The route from elemen-tary elements to the entire building seems long, but the knowledge on the dynamic response and damage to the structural elements and the ability of prediction is necessary. The required level of detail still has to be defined and depends on the type of risk that is considered.

Summarizing the results:

- The resistance curve of a structural element is suitable to characterize the properties of the element up to failure as well as for a loading–unloading cycle. The residual stiffness and deformation is represented. However, specific knowledge is needed to determine the resistance curve up to failure, or for the unloading phase, or for dynamic loading conditions. The required knowledge is only partially available. Differences between the resistance curve for static loading and the theoretically (FE) or experimentally derived resistance curve exhibit the combined rate effect in material and structural response.
- The SDOF engineering method to represent the dynamic response can be used for damage prediction if extensive damage and structural deformation occurs and dominates the damage assessment for the total building. For the general limitations of the SDOF method, see (Biggs, 1964; Weerheijm *et al*., 2005; Weerheijm and Lim, 2007). The FE-analysis clearly showed the limitations for the initial dynamic response phase, higher eigenmode responses and

related damage development never can be represented accurately by the SDOF system. If the RC-structure is properly designed and no early failure occurs, the influence on the later stage response up to failure is limited and the SDOF can be useful.

- The SDOF method represents the structural response of the element expressed in the displacement of one single point (1 degree of freedom). Consequently, the damage distribution within the element has to be derived from the value of the selected degree of freedom. In dynamics, this is not evident. Based on force equilibrium and assumed deformation shape, the damage distribution can be estimated. This work is currently ongoing at TNO with the experimental data and the FE-calculations as references.
- The test procedure that has been developed to derive the dynamic resistance of a slab up to failure in one single shock tube test is very well suited to study the dynamic response up to failure. The gained experimental data form a valuable reference for the theoretical methods.
- The LS-DYNA code and the KC-concrete material model were selected for the current study. Dynamic response, damage development and the residual static bearing capacity can be derived with the FE-tool. Simulation of the experiments has been performed successfully and the consequences of the simplifications in the SDOF approach were quantified. The main shortcomings of the FE-code are in the dynamic material model and especially for the softening, failure behavior under dynamic loading. This research area (Weerheijm and Doormaal, 2007; Vegt and Weerheijm, 2007) is relatively unexplored but without a proper representation in the material model, numerical prediction of the failure process under (extreme) dynamic loading cannot be accurate. It is also recommended to pay special attention to the bonding of the reinforcement in dynamics.
- Experimental validation of the (predicted) residual strength is recommended.

Next steps in the research programme are focused on the prediction of the consequence of the local explosion damage to the properties and residual functionality of the entire building.

4. Summary

The resilience of a city to natural or man-made disasters strongly depends on the vital infrastructure and the physical protection of people. To judge the vulnerability, to assess the resilience and identify effective countermeasures, risk assessment tools are needed.

In a bomb attack scenario, load prediction and damage prediction to the infrastructure are the essential elements in the risk assessment tool. Because the properties of the objects enable the functions, damage to the objects is directly related to the loss of functionality. A Dutch R&D programme has been defined with focuses on two aspects. First, the ability to quantify the explosion damage in terms of damage zones, volumes, and damage levels. Secondly, the possibility to couple the damage volumes and damage levels to the loss in functionality in time. The results on damage prediction obtained so far are given in the paper and summarised in Section 3.4.

The case of an extreme loading, such as an explosion, demands specific, uncommon knowledge. For example, (i) nonlinear design is needed for the extreme dynamic loading conditions, (ii) safety factors are well established for normal loading conditions, but in nonlinear designs, the safety factors and failure limit states are not evident, and (iii) knowledge on the dynamic material behavior up to failure is scarce.

Because of the extensive research needs and the need for new codes and standards for implementing research into practice for achieving urban resilience under extreme loads, international cooperation is needed.

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ENGINEERING METHOD FOR PROMPT ASSESSMENT OF STRUCTURAL RESISTANCE AGAINST COMBINED HAZARD EFFECTS

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Abstract: A general approach is proposed for prompt assessment of resistance of both structural elements and buildings as a whole under combined hazard effects. Proposed engineering approach is based on physical insights in the processes of loss of service performance of structural elements under the specific set of combined hazard factors —Impact-Explosion-Fire (IEF). Key element of the concept is the notion of "base" bearing structures, i.e., bearing elements that are involved and play a crucial role in providing general stability and geometrical fixation of a building under extreme conditions. A step-by-step algorithm for building resistance assessment is described. Virtual Reality-based computer realization of the proposed methodology makes the process of assessment convincingly visible and easy.

Keywords: hazards; resistance; combined effects; impact; explosion; fire; resistance; structure, building

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1. Objectives

Effective decision-making and successful countermeasures for any emergency situation are based on the appropriate level of:

- First-responders and emergency team skills and suitable equipment
- Effective rules and regulations
- Emergency situation understanding.

Together they provide successful emergency decision-making and countermeasure taking.

Our work basically is concerned with producing understanding of hazards in new, nonstandard emergency situations, like the WTC tragedy, but can also be applied in other directions.

Already during the first stages of an incident it is vitally important to have appropriate tools available for prompt assessment of hazards and vulnerability of structures. According to investigations and preliminary risk assessment provided by the research team of "Hazards and Risk Analysis for Aircraft Collision with High-Rise Building" (ABC) project in the years 2002 to 2004 (Kirillov and Pasman, 2004), building resilience appeared to be one the most important factors for decreasing possible injuries and loss of life.

Until now we do not have a useful methodology for prompt estimation of the effect of the most important hazard factors in force, of building ultimate resistance or of time duration to possible structure collapse. Detailed multiscale, multiphysics simulations of hazard effects require considerable computational and time resources.

We propose a rather simple engineering method and software for prompt assessment of structural resistance and durability based on empirical knowledge.

2. Engineering Method for Prompt Assessment of the Resistance of Structures and Buildings

2.1. INTRODUCTION

The tragic events in New York on September 11, 2001 by the terrorist attack on the World Trade Center (WTC) buildings, caused many political and social problems and also raised a number of engineering issues

(FEMA, 2002). One of the key engineering issues is assessment of the building capacity to resist the **C**ombined **H**azard **E**ffects of "**I**mpact-**E**xplosion-**F**ire" (CHE IEF) (Zabegaev and Roitman, 2001). On the basis of general physical considerations (Roitman, 2001; Pettersson, 1988; Barthélémy and Kruppa, 1978) of the mechanism of rapid loss of performance of quality of structural materials and structures in extraordinary situations an approach is put forward for an assessment of the ability to carry the loading. This "resistance resource" of buildings and structures to special combined effects of the "impact-explosion-fire" type is the subject of this study.

2.2. NOTION OF IEF-RESISTANCE OF BUILDINGS AND STRUCTURES

The IEF resistance of a structure defines its ability to keep its bearing and/or protective functions under combined hazard effects of the IEF type. In view of the incidental and combined nature of the effects in question on a building, assessment of its IEF resistance, as a rule, is to be performed on the basis of the limit state marked by the loss of bearing capacity, i.e., full collapse or inadmissible deformation.

In terms of the above reasoning, the IEF structural resistance may be considered as an index characterized by two criteria: non-attainment of the limit state, i.e., loss of the bearing capacity of the structure under CHE IEF:

$$R_{\text{ief}}(\tau_{\text{i ef}}) - S_{\text{i e f}}(\tau_{\text{ie f}}) = \Delta R_{\text{ief}}^{\text{res}}(\tau_{\text{i e f}}) > 0 \qquad (1)$$

$\Delta R_{\text{ief}}^{\text{res}}(\tau_{\text{ief}})$ being the residual resource ("reserve") of the bearing capacity of the structure at the instant of time τ_{ief} the structure under CHE IEF reaches its limit state. However, it should resist during the period τ_{ief} available for evacuation via fire egress, and other urgent measures, i.e.,

$$\text{if } R_{\text{ief}}(\tau_{\text{ief}}) - S_{\text{ief}}(\tau_{\text{ief}}) = \Delta R_{\text{ief}}^{\text{res}}(\tau_{\text{ief}}) = 0, \text{ then } \tau_{\text{ief}} = \tau_{\text{ief,r}}^{\text{act}} \qquad (2)$$

$\tau_{\text{ief,r}}^{\text{act}}$ being the actual (or true) IEF resistance of the structure, characterized by the period (in minutes) between the start of CHE IEF and the loss of the bearing capacity.

The IEF resistance of the building defines the ability of the building as a whole to resist the action of dangerous IEF factors and depends on the resistance of its principal structural elements to these loads.

The IEF resistance is the most important feature determining the consequence of aircraft crash in a building, supported by the evidence in behavior of the WTC towers in New York after the terrorist attack on September 11, 2001. The structure of WTC 2 (South tower) resisted to the combined effect of aircraft impact, fuel 'explosion' and subsequent fire during 56 min, i.e., the actual IEF resistance of this tower under the conditions of impact was *R*56. In case of the tower WTC 1 the crash resulted in a somewhat longer residual integrity and time to collapse and its actual IEF resistance limit was *R*103 (1 h 43 min). Just the minutes of residual integrity before collapse provided by the IEF resistance of the structure saved some thousands of people who were evacuated or rescued from the WTC towers and near-by buildings in the dangerous zone during this period.

2.3. GENERAL APPROACH TO ASSESSMENT OF IEF STRUCTURAL RESISTANCE

The essence of the proposed approach to assessment of structural resistance under CHE IEF resides in computations of changes of bearing capacity of undamaged and partly damaged structures and loads on them for various combinations of CHE, taking into account the behavior of structural materials under conditions considered. The aim of the computations is the determination of minimal values of the bearing capacity of principal structural elements $R_{\text{ief}}^{\min}$ and maximal loads $S_{\text{ief}}^{\max}$ on them (Zabegaev and Roitman, 2001).

If the minimal value of the bearing capacity under CHE IEF does not reduce to the maximal values of loads on the structure, see Figure 1, curve $R_{\text{ief}}(q^2; \tau_f)$, the limit state of the structure does not occur. The structure has a certain reserve of bearing capacity $\Delta R_{\text{ief}}^{\text{res}}$ (Figure 1). In this case, the IEF structural resistance is to be determined conform criterion (1). If the minimal value of the bearing capacity $R_{\text{ief}}^{\min}$ of the structure reaches the maximal level of loads $S_{\text{ief}}^{\max}$ it is subjected to, the IEF structural resistance is to be found by criterion (2).

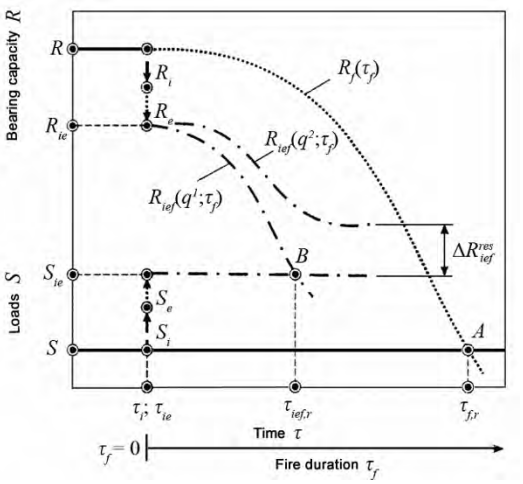

Figure 1. General chart of assessment of the IEF structural resistance under combined hazard effects of "impact-explosion-fire" type due to aircraft crash on building.

2.4. ENGINEERING METHOD FOR ASSESSMENT OF THE IEF STRUCTURAL RESISTANCE

The proposed engineering method for assessment of the IEF resistance of structures and buildings is based on the concept of "base" bearing structures, i.e., bearing elements that are involved and play a crucial role in providing the general stability and geometrical fixation of the building under conditions considered. For modern buildings, the columns, bearing walls, etc., may be considered as "base" bearing structures. It is logical to suppose that the IEF resistance limit will occur at the loss of bearing capacity of a certain "critical" number of "base" bearing elements with regard to their joint behavior under conditions considered.

The flowchart of the proposed engineering method is shown in Figure 2. It allows for the fact that aircrafts may be a source of CHE IEF, these may have a wide range of mass, geometrical, structural and other characteristics including speed, angle of attack, quantity of fuel,

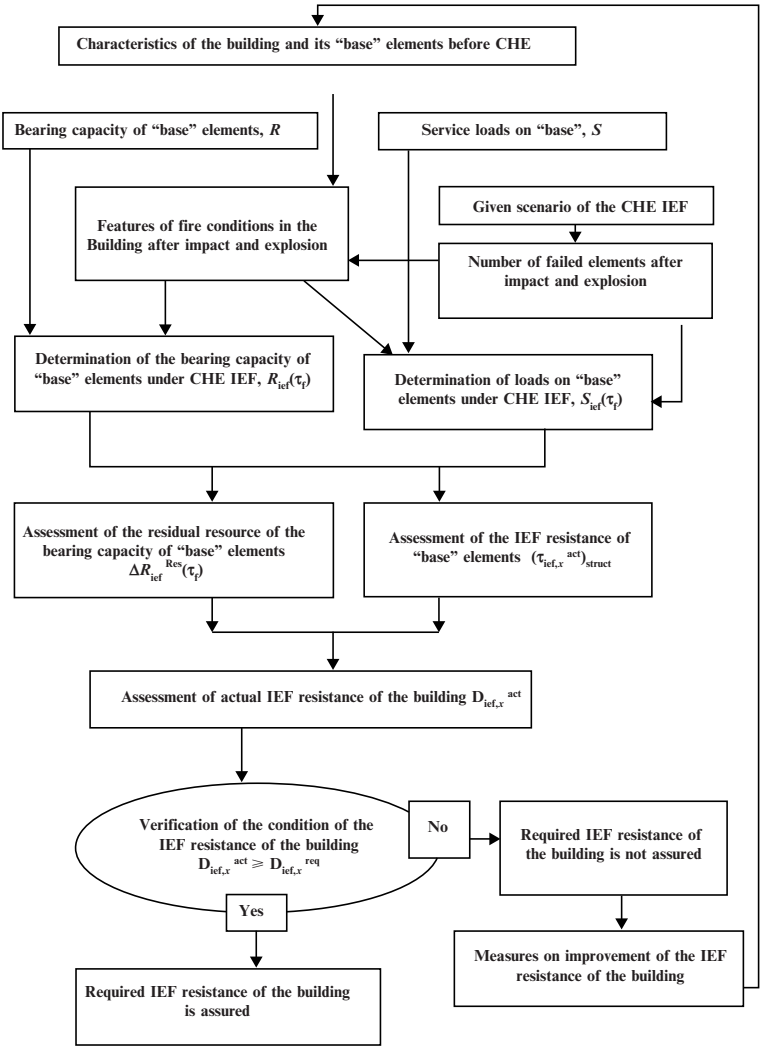
Characteristics of the building and its "base" elements before CHE
Bearing capacity of "base" elements, R
Service loads on "base", S
Features of fire conditions in the Building after impact and explosion
Given scenario of the CHE IEF
Number of failed elements after impact and explosion
Determination of the bearing capacity of "base" elements under CHE IEF, $R_{ief}(\tau_f)$
Determination of loads on "base" elements under CHE IEF, $S_{ief}(\tau_f)$
Assessment of the residual resource of the bearing capacity of "base" elements $\Delta R_{ief}^{Res}(\tau_f)$
Assessment of the IEF resistance of "base" elements $(\tau_{ief,x}^{act})_{struct}$
Assessment of actual IEF resistance of the building $D_{ief,x}^{act}$
Verification of the condition of the IEF resistance of the building $D_{ief,x}^{act} \geq D_{ief,x}^{req}$
No
Yes
Required IEF resistance of the building is not assured
Measures on improvement of the IEF resistance of the building
Required IEF resistance of the building is assured

Figure 2. Flowchart of the engineering method for assessment of the IEF building resistance.

etc. For engineering evaluations, it seems to be expedient, to express the diversity of CHE IEF effects on the building in terms of number of "base" structures that may lose (totally or partly) their bearing capacity after impact< subsequent explosion and fire. The proposed method may be used for solving problems of two kinds:

Problem of the first kind (direct problem)—Assessment of the IEF resistance of the "base" structures and the building as a whole for different scenarios of aircraft crash on the building. For solving this problem, three questions should be considered:

1. Determination of the IEF resistance of "base" structural elements of the building for the given scenario of CHE IEF
2. Determination of the actual IEF resistance of the building as a whole for the given scenario of CHE IEF
3. Evaluation of correspondence of the obtained value with the actual IEF resistance of the building, admissible risk requirements, safety of people and need to preserve the building (see Figure 2).

Problem of the second kind (inverse problem)—Determination of admissible number of "base" structural elements that may have failed or damaged in the crash, on the basis of given (normalized) IEF resistance of the building. The normalized level of the IEF resistance is to be found on the basis of admissible risk levels, safety of people and preservation of the building. Problems of studying consequences of CHE associated with aircraft crash may be assigned to this kind of problems.

2.5. ANALYSIS OF STRUCTURAL BEHAVIOR OF WTC 1 TOWER UNDER CHE IEF CAUSED BY AIRCRAFT IMPACT ON THE BUILDING ON SEPTEMBER 11, 2001

2.5.1. *Basic Data*

Characteristics of "base" structures:
columns of external walls (perimeter columns) (FEMA, 2002): n^p = 240; a^p = 0.35 m; δ^p = 0.0076 m; δ^p_{is} = 0.04 m (vermiculite); Columns of internal core : n^c = 47; a^c = 0.40 m; δ^c = 0.03 m ; δ^c_{is} = 0.03 (vermiculite); Column fire resistance $\tau_{f,r}$ = R180 (FEMA, 2002); Critical temperature of heated column metal under fire: T^{cr}_m = 500°C.

Features of Boeing 767-200ER

Maximal weight—179,200 kg, speed—850 km/h, wingspan—47.5 m, length of aircraft—48.5 m, maximal fuel-carrying capacity—91,000 l, height from the land to the tail top—16.15 m, space between engines—15 m, volume of wing tanks—19 × 4.5 × 0.85 m.

Consequences of the aircraft crash on building (FEMA, 2002; Zabegaev and Roitman, 2001)

IEF resistance of the WTC 1 tower during the 9/11 events: $D^{act}_{ief,r}$ = R103; $n^{p}_{d} = 55$; $n^{p}_{u.d} = 185$; $n^{p}_{u.d(+f)} = 100$; $n^{p}_{u.d(–f)} = 85$.

These guess values are based on analysis of original structural drawings, videos and photos.

It is **asked** to assess the number of "base" structural elements of internal walls and internal core of the building under various states that assured the given value of the IEF resistance of the building ($D^{act}_{ief,r} = R103$) after the aircraft impact, fuel explosion and subsequent fire: $n^{c}_{d} = ?$ $n^{c}_{u.d} = ?$ $n^{c}_{u.d(+f)} = ?$ $n^{c}_{u.d(–f)} = ?$ $n^{c(–is)}_{u.d(+f)} = ?$ $n^{c(+is)}_{u.d(+f)} = ?$

2.5.2. *Development of Scenario of the Aircraft Crash Consequences*

In this case, the proposed engineering method of assessment of the state and behavior of the building elements under CHE of the IEF type is used for solving the inverse problem. This means that on the basis of given IEF resistance of the building, it is necessary to assess the number of "base" structural elements of the building in various states

TABLE 1. Assessment[a] of structural elements, their state, number and their location (From Zabegaev and Roitman, 2001)

State of "base" structural elements of the building	Number of "base" structural elements of external walls				Number of "base" structural elements of internal core	
	North side	East side	South side	West side	Total	
Columns under normal service	60	60	60	60	240	47
Columns failed by aircraft crash and explosion	37	5 + 5	8	—	55	10[a]
Columns undamaged after impact and explosion	23	50	52	60	185	37[a]
Undamaged columns affected by fire	10 + 5	10 + 10	15 + 5	45	100	20[a]
Undamaged columns beyond the fire	8	30	32	15	85	17[a]

[a]The assumed value for the scenario version under consideration.

that have assured this resistance after aircraft impact, fuel explosion and subsequent fire.

The estimated (see details in Zabegaev and Roitman, 2001) number of "base" structural elements of the WTC 1 tower under various states after the impact, explosion and fire considered in the design scenario is given in the Table 1.

2.5.3. *Computation Results*

The computations include (Figure 3):

- Assessment of changes of relative load on undamaged external columns and internal core after collapse of the part of columns due to aircraft impact and subsequent 'explosion' (Figure 3a): $S^{p}_{ie}/S^{p} = 1.29$; $S^{c}_{ie}/S^{c} = 1.27$;
- Assessment of heating of undamaged columns under fire as it broke out after aircraft impact and 'explosion' (Barthélémy and Kruppa, 1978; Yakovlev, 1988; Cape Boards Limited, 1993):

  For external walls and internal core with undamaged fire protection (fireproofing), $T^{p(+is)}_{m\,(+f)}$ (see curve *4*, Figure 3c);
  For external columns with loose fire protection after impact and 'explosion': for $H_p/A = 135\ m^{-1}$ (H_p/A being heated perimeter area), $T^{p(-is)}_{m(+f)}$—see curve *2*, Figure 3c; the same, for core columns: for $H_p/A = 36\ m^{-1}$; $T^{c(-is)}_{m(+f)}$—see curve *3*, Figure 3c, assessment of decreased values of critical temperature of heated columns with regard to increased load on undamaged columns after aircraft impact and 'explosion':

  for $S^{p}_{ie}/S^{p} = 1.27$ $T^{cr}_{m} = 428°C$ (see Figure 3b);

  for $D^{act}_{ief,r} = R103$ $T^{cr}_{m} = 310°C$ (see Figure 3b).

  Assessment of the IEF resistance of undamaged columns: with fire protection under fire effect only (see Figure 3c)—for $T^{cr}_{m} = 500°C$ $\tau_{f.r} = R180$.

  With fire protection in regard to column load changes after impact and explosion (see Figure 3c): for $T^{cr}_{m} = 428°C$ $\tau^{p(+is)}_{ief,r} = R150$; $\tau^{c(+is)}_{ief,r} = R150$.

Hence, if all columns of external walls and internal core had conserved their heat protection, the IEF resistance of the WTC 1 tower would be $D^{(+is)}_{ief,r} = R150$, and if all columns of the WTC 1 tower had

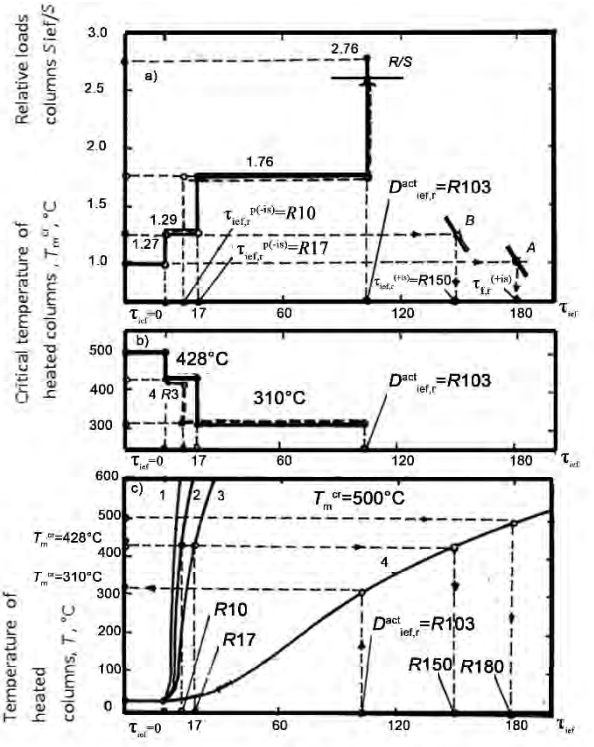

Figure 3. Design method based assessment of behavior of principal structural elements of WTC-1 tower under CHE IEF, as consequence of aircraft crash on the building: (*a*) change of relative values of the loads of external columns (—) and core columns (---) after impact, explosion and subsequent fire; where *S*ief—load on structure under CHE IEF; *S*—load on the "base" structure under normal conditions; (*b*) change of critical temperature of heated external columns (—) and core columns (---) for varying stages of CHE IEF; and (*c*) change of temperature of these elements against the duration of fire developed after impact and explosion; *1*—temperature schedule of the fire, under consideration; *2*—heating curve for an external column after fire protection loss due to impact and explosion; *3*—heating curve for a core column after fire protection loss due to impact and explosion; *4*—heating curve for columns with undamaged fire protection.

lost their heat protection after impact and explosion, their IEF resistance would be $D^{(-is)}_{ief} = R10$ and $R17$.

At the same time, the actual IEF resistance of the tower was $D^{act}_{ief,r} = R103$. This means that only part of the "base" elements has

conserved their heat protection and the rest of elements have lost it after impact and 'explosion.'

Assessment of the number of external and internal columns that conserved or lost their fire protection after impact and explosion.

This problem was solved by stepwise approximation procedure, i.e., some values of the number of columns with loose fire protection $n^{(-is)}_{u.d(+f)}$ was given and some values of the number of columns that lost their IEF resistance at the instant of time $\tau_{ief,r} = R10$ and $R17$ and, thus, increased the relative load on columns that conserved the fire protection.

The further computations permitted to find some values of critical temperature of external and internal columns depending from the change of the relative load on them and, respectively, from their number.

From the condition: for $\tau^{act}_{ief,r} = R103$ $T^{cr}_{m} = 310°C$, the values sought were found:

$$n^{p(+is)}_{u.d(+f)} = 53;\ n^{p(-is)}_{u.d(+f)} = 47;\ S^{p}_{ief}/S^{p} = 1.74 \text{ (see Figure 3a)}$$

$$n^{c(+is)}_{u.d(+f)} = 10;\ n^{c(-is)}_{u.d(+f)} = 10;\ S^{c}_{ief}/S^{c} = 1.74 \text{ (see Figure 3a)}$$

TABLE 2. State of the base elements and their distribution over external wall and core

	State of "base" elements of the building	Number of "base" elements of external walls	Number of "base" elements of internal core
1	Normal state of columns before crash	$n^{p} = 240$	$n^{c} = 47$
2	Columns failed due to impact and explosion	$n^{p}_{d} = 55$	$n^{c}_{d} = 10$
3	Columns undamaged after impact and explosion	$n^{p}_{u.d} = 185$	$n^{c}_{u.d} = 37$
4	Columns affected by fire	$n^{p}_{u.d(+f)} = 100$	$n^{c}_{u.d(+f)} = 20$
5	Columns affected by fire with fire protection lost after impact and explosion	$n^{p(-is)}_{u.d(+f)} = 47$	$n^{c(-is)}_{u.d(+f)} = 10$
6	Columns affected by fire with undamaged fire protection	$n^{p(+is)}_{u.d(+f)} = 53$	$n^{c(+is)}_{u.d(+f)} = 10$

Analysis of the state and behavior of WTC 1 tower under CHE IEF as consequence of the aircraft crash at the building on September 11, 2001 by the proposed method, has shown that, for the chosen alternative

of the event scenario, the resistance duration of the building against CHE IEF (its IEF resistance) $\tau_{ief,r}^{act} = R103$ depended on the following number of the "base" bearing elements, in one state or another (Table 2).

3. Software Tool for Estimation of Building Resistance to Influence of the Combined Hazard Effects

A special computer code (Lukashevich, 2004) for estimation of building resistance to combined factors—Impact-Explosion-Fire (IEF) loadings was realized according to methodology, described in Section 2.4.

3.1. UNIVERSAL PROBLEM-ORIENTED DATA STRUCTURES

A universal virtual model of high-rise building in the form of a computer description was developed. The main elements and characteristics of a building were implemented as universal (computer and operation system independent) description.

According to the geometrical description of a selected high-rise building, a Virtual Reality prototype using universal object structure was generated.

3.1.1. *High-Rise Building Universal Object Structure*

Every element of the building construction is also an object with several properties. So the library gives the user a universal structure for description of a definite high rise building.

Already at the stage of creating the initial Virtual Reality (VR) building prototype most characteristics of the objects are described on the basis of design and construction papers. The remaining features of the objects are defined after studying the specific building by experts in different domains and providing software simulations.

3.1.2. *Virtual Reality Prototypes of Typical High-Rise Buildings*

Initially, the Virtual Reality prototypes for two representative kinds of high-rise buildings were prepared. First type is related to buildings, where concrete elements provide bearing capacity. Second type encompasses high rise buildings, where main bearing elements are steel columns, trusses, etc. (model case—the WTC building).

3.2. MULTILAYERS METHOD FOR DETAILED HIGH-RISE BUILDING PROTOTYPING

For effective management of virtual prototypes, all geometric objects (construction elements) are grouped into logical layers corresponding to their functionality:

- Urban environment and architecture design (can be imported from external sources (FEMA, 2002))
- Primary load-bearing members (columns)
- Secondary load-bearing members (walls, floors…)
- Fire-propagation elements (elevators, utility channels…)
- Emergency exit stairways

By means of object oriented programming language a UML description and an object model of the buildings is developed. Subsequently a XML actualization of the object model of the building is realized. An example of virtual prototype is shown in Figure 4.

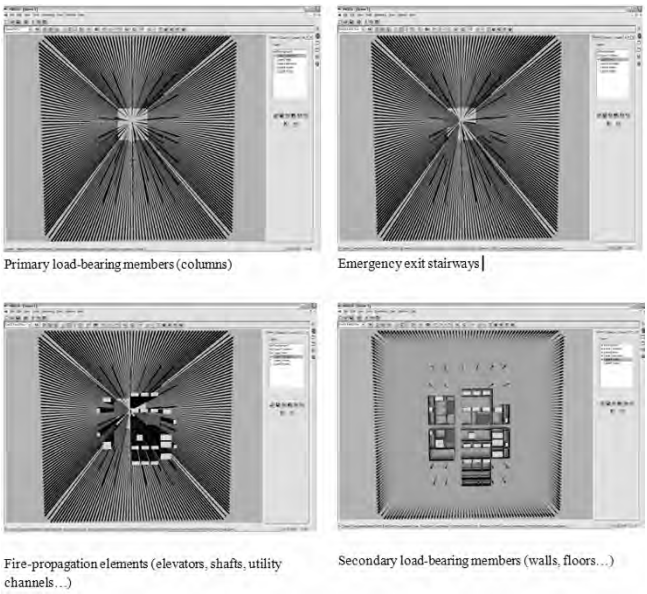
Primary load-bearing members (columns)
Emergency exit stairways
Fire-propagation elements (elevators, shafts, utility channels…)
Secondary load-bearing members (walls, floors…)

Figure 4. Logical layers structure for Virtual Reality (VR) detailed model of WTC. construction (perspective top view). VR also enables drawing of 3D pictures.

3.3. STEP-BY-STEP PROCEDURE OF BUILDING RESISTANCE EVALUATION

Step 1: Using an interactive 3D prototype a user has to select the floor number to locate Impact origin.

Step 2: For a selected floor a user has to select or mark load-bearing construction elements according to the next simple rules:

- Destroyed load-bearing elements (columns) have to be marked as members of "**n_X_d**" groups. Where X have to be letter "**c**" for "core" members and "**p**" for "perimeter" members

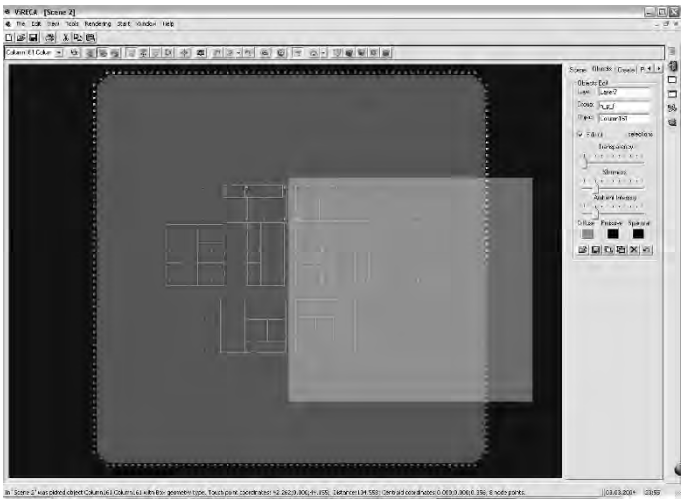

Figure 5. Selecting of construction elements as destroyed, damaged and affected by fire via VR-based user interface.

- Load-bearing elements (columns) which lost fire-proofing, but which are still functional have to be marked as members of "**n_X_f_fp**" groups. For letter X is substituted "**c**" for "core" and "**p**" for "perimeter" members.

Construction elements, affected by fire have to be marked as members of "**n_X_f**" groups (Figure 5).

Step 3: Resistance estimation. Total building resistance is found by running the software module "Resist" directly from the Virtual Reality environment. The number of selected bearing elements (columns) is transferred into the solver automatically.

Changes of relative load on undamaged external columns and internal core after CHE IEF are presented in Figure 6. The black band means achieving collapse conditions. For the detailed and more specific calculations the user can vary the construction parameters.

Step 4: Setup fireproofing properties of construction elements with fire protection. To change the distribution click in the plot area, see Figure 7, and fill the Table.

Step 5: Setup fireproofing properties of construction elements without fire protection.

Step 6: Check or set number of destroyed external columns.

Step 7: Check or set number of external columns affected by fire that preserved fire proofing.

Step 8: Check or set number of external columns affected by fire that lost fire-proofing.

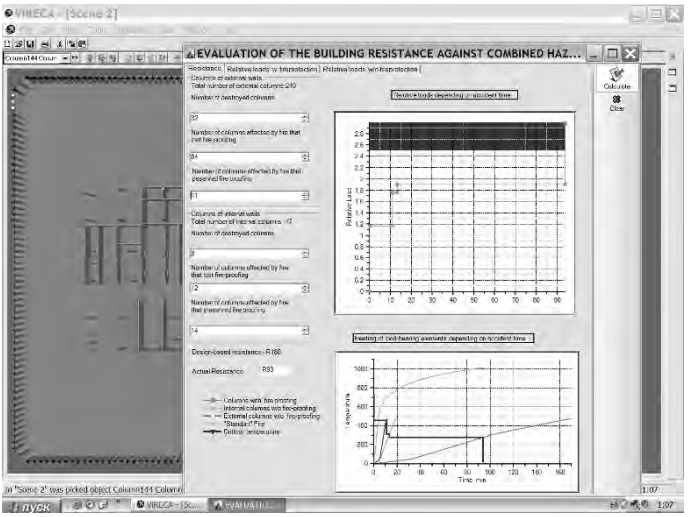

Figure 6. Building resistance and accident history evaluation.

Step 9: Check or set number of destroyed internal columns.

Step 10: Check or set number of internal columns affected by fire that preserved fire proofing.

Step 11: Check or set number of internal columns affected by fire that lost fire-proofing.

Step 12: Make a new calculation of building resistance with defined parameters.

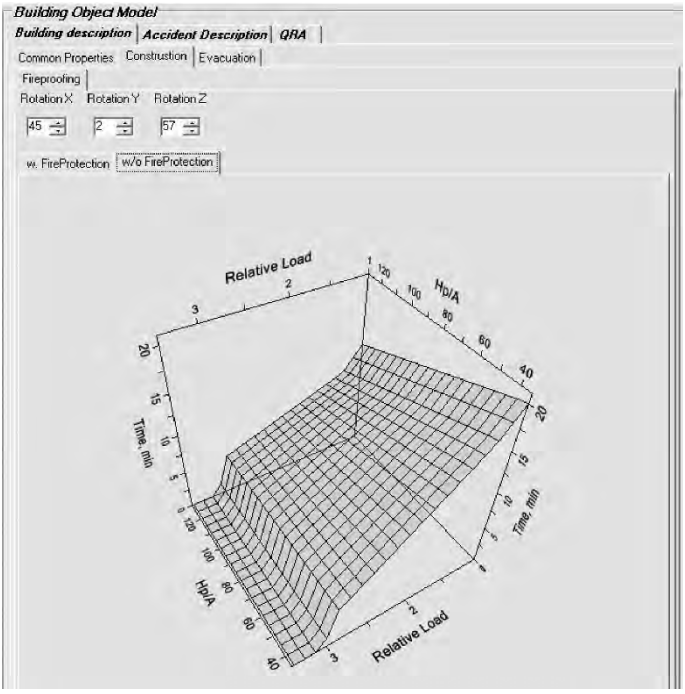

Figure 7. Properties of constructions with fire protection.

4. CONCLUSIONS

The proposed general approach and engineering method of assessment of the IEF resistance of structural elements and buildings under CHE IEF caused by aircraft crash on a building allows:

- A rather simple description of the processes defining the ability of buildings to resist to CHE IEF
- Assessment of the real danger and risk of an aircraft crash in a building
- Elaboration of sound protective measures for assuring the required resistance of buildings against possible CHE IEF

In fact the actual point is the possibility to "reconstruct" the pattern of state changes for principal structural elements of a building, which are sufficient for the engineering assessments under the conditions considered.

A virtual model of a high-rise building in the form of a platform-independent description is created. The main elements and characteristics of the building are stored as a universal object structure.

Virtual Reality prototypes of WTC 1 & 2 buildings and model "concrete" high-rise buildings have been developed. Virtual Reality prototypes were integrated with the universal object structure describing the characteristics of the main construction elements.

A prototype of a special computer code for estimation of building resistance to the effects of the combined factors—Impact-Explosion-Fire (IEF) was developed and implemented.

Verification both by empirical data and methodology in a sufficient number of environmental structures is the most important next step.

The engineering method of structural resistance has to be verified providing both detailed theoretical and experimental research.

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THEME 4

FUTURE STRATEGIES

Collage by Igor Lukashevich

A MULTIHAZARD APPROACH TO INSURE RESILIENT URBAN STRUCTURES

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Abstract: This paper provides background on a multihazard research approach for protecting urban infrastructure systems. This effort is vital for the development of more effective solutions to problems that are currently addressed primarily with conservative, and/or empirical approaches. The expected outcome will have a profound effect on national and international peace, prosperity, and security. Essential work must be conducted in several important areas that include scientific and technical topics, as well as socio-economics and public policy.

Keywords: multihazards; natural disasters; terrorism; accidents; protection; technology; research; development; urban infrastructure

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1. Introduction

Properly functioning civil-infrastructure systems are vital to the well-being of civilization worldwide. They include the entire built environment in our urban areas, including essentially every constructed facility which we use for shelter, food, transportation, business, health care, power, telecommunications, water supply, and waste disposal. Most of the existing infrastructure systems are highly vulnerable to natural and human-induced hazards, as several recent examples have shown (e.g., the 1994 Northridge earthquake, the terrorist attacks on 11 September 2001 in the USA, the Tsunami in 2004, hurricane Katrina in 2005, etc.). Although many such hazards cannot be controlled, forethought on how to develop resilient constructed facilities to resist them is possible. However, such foresight is often lacking, primarily because the hazards were underestimated during the planning and design processes. Moreover, with the advancing age of much of our infrastructure, systems have decayed as a result of deferred maintenance. These vulnerabilities are further intensified by possibilities that natural hazards are intrinsically correlated and occur sequentially (e.g., Katrina's wind field caused a storm surge that overtaxed the New Orleans Levee System, the Kocaeli earthquake caused a fire that destroyed the Tupras oil refinery, a vehicular impact caused an intense fire that destroyed the I-80 approach to the San Francisco—Oakland Bay Bridge). Hazard sensitivities are exacerbated all the more with scenarios that include terrorist attacks during times of weakness during or following an extreme natural event.

With appropriate research and development, vulnerability to extreme hazards can be appreciably diminished. Civil infrastructure systems can be constructed or retrofitted to exhibit the necessary resilience to survive extreme events without significant disruption to society. A comprehensive plan for addressing infrastructure protection against abnormal short duration dynamic loading incidents (e.g., blast, shock, impact and terrorism) was presented recently (Krauthammer, 2007), and similar approaches can be envisioned in each hazard area, separately. Further more, such an approach could be expanded to address infrastructure protection against multihazards. This formidable challenge can be met in part through a comprehensive research and development (R&D) program to transform the implementation of

critical infrastructure systems to resist specific hazard combinations and thus enhance the quality of life, economic prosperity, safety, and security. A transformational engineering approach must be developed that will enable society to build more resilient and robust civil-infrastructure systems. Whereas the new research will not create new infrastructures per se (that would take billions of dollars), new engineering design approaches and tools will emerge from this vital effort in multihazard research that will enable safer, more economical, and more secure infrastructure systems.

Because multihazard safety is a public right, research towards it should be funded by the public rather than only through commercial enterprise. Thus, in the context of this concept approach, funding should be provided by government agencies (federal, state, and local). In addition, collaboration will be achieved with construction industry partners contracted by government agencies on infrastructure projects, as well as engineering and architectural practitioners, and the insurance industry to enhance the implementation potential of research results. In this regard, a Stakeholder Advisory Board should be formed upon the establishment of the effort to help direct the strategic research plan before projects are initiated.

The proposed multinational research effort should function as an International Center to develop a comprehensive paradigm for multi-hazard mitigation of civil-infrastructure systems, taking advantage of existing expertise on multiple hazards—blast, fire, wind, storm surge, impact, and earthquake. The distinguishing feature of the multinational effort, and that which is vital to its success, will be the incorporation of expertise on various research thrusts into an all-inclusive resource that addresses hazards within a risk-consistent framework. This new paradigm has two broad objectives:

1. Design new technologies for hazard-resistant infrastructure to address multiple hazards, while maximizing economies of scope. Separately developed hazard designs will be replaced by designs based on comprehensive, synergistic research among experts in multiple hazard areas.
2. Develop a practical and rational decision tool to present risk-reduction options in terms of quantitative and qualitative attributes. These attributes include the synergistic technology from the first objective, the cross-purpose hazard-mitigation measures that cannot be eliminated from the building design, direct and indirect costs,

and human/societal preferences for cost, convenience, safety, and aesthetics.

Aggressive technology transfer, training and education will guide Center's integration with broader institutions. The Center will cultivate relationships with appropriate academic institutions, government, and the private sector. From the very outset, private-sector dialogue should include input and review from investors and potential industrial partners—allowing the Center's work to be readily adopted by industry.

2. The Advantage of the Proposed International Center

Hazards can result in extreme loss of life and property, disrupt economic well-being and the overall quality of life, not just at the site of hazard impact, but across a large geographic area. Because of the extreme magnitude of these potential losses (in the hundreds of billions of dollars) and the fragile condition of much of society's infrastructure systems, a significant opportunity exists to reduce such losses through coordinated interdisciplinary research conducted through the context of an international research center. The potential loss reductions are, at least, hundreds of times the research investment. Research talents that have traditionally been categorized into hazard specific initiatives can be combined to estimate multihazard potential and likelihood, and develop mitigation methods based on consistent risk across entire infrastructure systems.

With more demanding building regulations and improved construction methods and materials, significant progress has been made over the last three decades in the design of hazard-resistant structures, but the improvements have been overwhelmingly hazard-specific (e.g., fire, earthquake, hurricane, flood, blast, impact, etc.). As a result, multihazard design remains remarkably underdeveloped. In the relatively few cases where it has been attempted, the result was not comprehensive protection of the structure but rather over-design and impractical costs. The fault in such plans is that they combined design features for different hazards without understanding the synergistic effects of such combinations. Such plans combined engineering parameters from different hazard areas, but they neither considered nor provided an all-inclusive perspective. The complexity of multihazard design and the

associated high cost of mitigation underline the need to develop a more-robust treatment of this critical problem. Having an efficient process to assess the combined risks involved and to optimize multihazard planning, design, and retrofit for civil infrastructure is a necessity now more than ever. One must focus on designing infrastructure systems from a comprehensive, multihazard viewpoint rather than individual hazards. This includes not only structural considerations, but also assessments of trade-offs among multiple factors based on the relative risks. A comprehensive risk assessment must incorporate design trade-offs by evaluating such criteria as the risk of a particular hazard, the potential loss of life, damage to the infrastructure, human behavior, and long-term socio-economic impact. This entails developing a synergistic, multihazard cost-benefit analysis for the concurrent design of safety and security systems in buildings, which analysis industry does not yet possess.

3. An Outline for a Strategic Research Plan

Center research should be directed by real needs. No research should be conducted unless it has a direct relation to the development of more-resilient infrastructure systems, and thus in diminishing likely consequences of a hazard. The entire effort can be envisioned as parallel activities conducted in a three-plane-space, as follows:

- Technology Integration: Technologies will be integrated through research projects that reside on the top plane. These will include projects to develop an all-encompassing, unified decision framework and integrated risk-management approaches that practitioners and non-technical decision-makers can use to establish strategies for hazard-resistant infrastructure construction.
- Technology Base: Technologies required to enable the development of the top-level milestones reside on the middle plane, and will include methods for assessing multiattribute risk, combining various risk scenarios and estimating risk reduction. Cyberinfrastructure technologies will be developed for integrating system-level research results.
- Knowledge Base: Basic knowledge necessary for the development of these enabling technologies will be acquired through research

projects shown on the bottom plane. These projects will include engineering characterizations of various hazard threats, mitigation measures, and damage estimation tools. Because extensive research on response of structures to individual hazards has been performed or is currently underway through other sponsorship, knowledge development outlined on the bottom plane will be a leveraged effort. Research on economics and public policy will be conducted to develop basic knowledge of how societies can benefit from recognizing multihazards, what impediments to change must be addressed with stakeholders, and what policy options may exist. Knowledge developed in this regard will be useful for developing decision frameworks and integrated risk management approaches. These bottom-plane projects are needed to develop the integrated risk management and unified decision-framework technologies on the top plane.

Center research should be organized to address four research thrusts:

1. Hazards and Response
2. Risk Assessment Technology
3. Socio-Economics, and Public Policy
4. Decision Analysis for Integrated Risk Management

The thrust on integrated risk management will be central to the other three, since that research is systems-oriented and is needed to integrate technology developed through the other thrusts. Thus, research on integrated risk management must not only identify needed research of the other thrusts but also rely on milestones and deliverables of those thrusts. Complementarities among these thrusts will help prioritize the proposed Center's research and provide the comprehensive perspective needed to optimally build infrastructure in a risk-consistent framework. More specifically, the Center should unite the hazard areas across a risk-assessment axis and thereby fundamentally change the way civil-infrastructure systems are planned, designed, constructed and retrofit to handle multiple hazards. The four thrust areas, are briefly discussed next.

4. Hazard and Response

The transformation of critical civil-infrastructure systems to resist multiple hazards requires the quantification of specific hazards or threats to these systems, the resultant effects or damage, and appropriate mitigation measures. This includes the quantification of risks associated with cumulative losses over the lifetime of the system due to more frequently occurring events (e.g., downbursts, tornadoes, modest earthquakes) in addition to those risks associated with extreme events (e.g., severe earthquakes, hurricanes, terrorist attacks). While hazard-structure interaction has been widely investigated for single hazards or more than one hazard in isolation, the present effort should focus on the consideration of a multihazard framework. This framework needs to consider the "hazard map" of today, as well as the future, which could be driven by various changing conditions (e.g., climate change, coastal population migration, changing seismicity, terrorism, etc.)

The fundamental Knowledge Base developed within this thrust will enhance the understanding of load effects and system response to multiple hazards, specifically identifying cross-hazard commonalities, which will feed the Technology Base focused on multihazard risk assessment. This knowledge base will draw heavily from the international expertise in monitoring, modeling and simulation. Further, the validation using full-scale test beds within the Technology Integration plane will be facilitated by this thrust to further evaluate the interactions between multiple hazards and complex infrastructures in an integrated risk-management and decision-making scheme. Research and development activities should include the following:

- Defining for threat environments (frequency, intensity, duration, geography) and commonalities in ensuing loads across hazards
- Developing tools for estimating system performance or resulting damage/loss for a given hazard and identify commonalities across hazards
- Assessing mitigation measures for individual and multiple hazards, including associated costs, and identify commonalities across hazards and
- Developing procedures for validation using full-scale test beds to characterize hazards and hazard-induced response for various risk-mitigation options for Technology Integration

Performance-based engineering has recast philosophies to consider additional limit states associated with more-frequent events. The Center should advance the state of the art further by rationally integrating the provision for handling multiple hazards in system design to minimize accumulated risks over the lifetime of the system. Two of the primary barriers to a multihazard framework lie in the conventional mindset that (i) a multihazard approach by default results in a suboptimal design, and (ii) that hazards lack sufficient commonality to be treated in a multihazard approach. Both of these barriers stem from mindset of the worst-case, single-hazard scenario, which does not consider the accumulated risk over the structure's lifetime or the notion of evolving hazards. This paradigm shift can only be facilitated through the combined efforts of the Center's team. This will be enabled by this thrust's efforts to identify commonalities within the various hazards, their impacts, and mitigation options to provide a unified multihazard approach to risk mitigation. Potential research projects include: Characterization of dynamic load effects on civil infrastructure systems; Damage scenarios in civil infrastructure; Development of cost-effective mitigation strategies for civil-infrastructure, etc.

5. Risk Assessment

The primary objective of this thrust should be to provide the explicit quantitative and qualitative methods and software tools to characterize hazards and mitigation options in a risk framework. The risk framework will be multiattribute, covering the quantitative likelihood of occurrence of hazards and their severity; infrastructure subsystem risk and subsystem-dependency risk; infrastructure-damage states; cost implications of property loss; commercial impact; casualty expectation; and mitigation options. To achieve this primary objective, several other goals must be reached. These include the following: (i) incorporating emergency preparedness and response into the quantitative/qualitative multihazard risk assessment; and (ii) understanding and characterizing mitigation options for building codes and standards in terms of risk reduction and stakeholder involvement/constraints. This thrust should provides the overarching scientific and mathematical methods to tie the diverse physical and engineering knowledge and practices, the combination of multihazards, and the crucial cost-benefit analyses and

stakeholder positions and constraints into a unified, communicable, and defensible perspective.

One should expand and transform the standard, single-hazard risk-assessment framework by (i) addressing a structure's risk from the totality of multiple-hazard initiation, propagation, and mitigation; (ii) incorporating emergency preparedness and response into a multihazard analysis framework; (iii) designing and implementing a quantitative risk-assessment tool that addresses several hazards; and (iv) providing a methodology and computational environment for systematic and multihazard-inclusive risk-based assessment of design trade-offs via sensitivity analyses. Specific challenges to this effort include the following:

- Development of a unified multidisciplinary and multihazard risk modeling approach
- Harmonization of metrics for various hazards
- Development of methods for treating risks that evolve over the life of the structure and
- Development of optimal emergency preparedness and response for multiple hazards

Current methods and tools of conventional probabilistic risk assessment have a number of limitations, as they are, for instance, more effective in modeling hardware systems of components, and better suited for risk assessment during the operational rather than the design phase. These limitations must be removed, since infrastructure systems need to consider the entire environment by addressing the physical, socioeconomic, and the regulatory and oversight environments.

One of the most important technical barriers this thrust will address is to incorporate the physical parameters and models pertaining to both hazards and their effect on civil structures into a probabilistic risk framework—a common ground. The ultimate purpose is to develop new materials, technologies, and designs for hazard-resilient infrastructure. Therefore this thrust must be intimately involved in the hazard and engineering modeling and characterizations within the Hazards and Response Thrust, and will be firmly involved in the test-bed applications. As envisioned, inputs from the other thrusts will be needed to help investigate, from a risk perspective, economically viable mitigation options. The needed methodology should provide a consistency

of risk characterization and evaluation across various hazards, and an interface between engineered systems physical response and human/organizational/societal response. The enabling technology to be developed in this thrust is the multihazard, multiattribute risk-analysis software, which will enable the Center to conduct the related research and development tasks while forming the foundation of a commercial version by private firms.

6. Socio-Economics and Public Policy

The proposed International Center approach is based on the premises that risk-based, multihazard design offers substantial societal benefits over the status quo, and that it is possible to change stakeholder behavior to realize those benefits. One needs to assess the potential societal gains from risk-based, multihazard design, evaluate public policies that would align institutional incentives with multihazard design goals, and engage opinion leaders in on-going transition strategies. A transition from prescriptive to performance-based design criteria could yield greater cost-effectiveness for any particular structure and greater incentives for innovation in the construction industry. For such a transition to occur, however, these benefits in cost-effectiveness and innovation must exceed the significant costs of developing and implementing the new paradigm. Unfortunately, to date, little work has been done to estimate the net benefits of wholesale adoption of performance-based design. One must address this issue in sufficient detail, and assess how legal, regulatory, and institutional forces per-petuate the status quo, and evaluate alternative policies and incentives required to change it. Projects in this thrust area should focus on the goal of developing wider acceptance and adoption of the Center's research and outcomes, and should include: Net benefits assessment of applying a risk-based, multihazard paradigm to the design of civil infrastructure; Innovation benefits of multihazard design; Setting legitimate public policy goals; Stakeholder engagement and roadmap for change, etc. The projects within this thrust should have a common purpose: establishing and lending intellectual support to an analytical-deliberative process on the transition to risk-based, multihazard design, and many of the projects within this thrust should reinforce and benefit each other.

7. Decision Analysis for Integrated Risk Management

The Center should develop the enabling and transforming technologies (e.g., software, building design, methodologies, retrofit strategies and practices) to evaluate and optimize multihazard assessment, design, and retrofit for critical civil infrastructure. In support of the Center goals, this thrust should consider using a decision-analysis framework to integrate decision-makers' values with engineering, cost, and risk information, to provide insight into the optimal selection of multihazard-resistant measures for individual buildings and other structures. The performance metrics, the mitigation options that would be considered, and the combination of mitigation options that will be selected need to be linked to performance requirements, and preferences of the key decision-makers (and ultimately society). These aspects need to reflect attitudes toward a potentially broad set of multiattribute values, the temporal distribution of costs and benefits (life-cycle analysis), and uncertainty. The uncertainty occurs not only with the timing and strength of a variety of stressors, but also with ability of the infrastructure to withstand the stressors and to be recovered from a damaged state. The problem is further complicated by the fact that planning and design alternatives must be compared to a base design and that the true measure of performance is in the difference in such distributions (e.g., proposed designed minus base design). Because the decision space for multihazard design is so complex, it is unrealistic to expect to create a tractable decision system capable of optimizing the selection of risk-reduction measures across all hazards for any infrastructure system. The goal of this thrust should be to identify areas of the decision space in which a modest amount of integrated decision analysis can provide the most valuable insights into multihazard trade-offs and synergies. Developing a practical set of decision-analysis tools for choosing among alternative consequence-reduction methods involves a number of trade-offs between system robustness, performance, implementation and/or recovery time, cost, and understandability. Learning the right balance in these trade-offs requires both experience in a real-world setting such as our test bed as well as ongoing dialogue with stakeholders to gauge their preferences.

The success of this thrust depends on engagement of the research program with practitioners. If the products of this thrust are to be embraced by practitioners, it is vital that investigators understand the decision perspectives of practitioners and the constraints under which they operate. The activities of this thrust will be conducted in close coordination with key stakeholders, who will engage engineering and industrial firms to plan, design, and construct actual infrastructure systems based on the state of practice and prevailing standards.

Performance-based design of structures has been making steady headway in recent years, as standards for building protection are increasingly expressed in terms of performance metrics. Algorithms for optimizing design choices under performance goals have been proposed for some hazards including fire and earthquake. So far, however, these proposals have not embraced multiattribute decision analysis as an organizing discipline, nor have attempts been made to integrate decisions on hazard resistance across multiple hazards. This thrust would formulate decision-analysis methodologies that are tailored to risk and engineering aspects of multihazard protection, while incorporating more "soft" constraints such as emergency preparedness and response capacities. The envisioned method will be designed from the start to incorporate decision-makers' (or the public's) interests and values, thus advancing prospects for true risk-based performance standards for built structures.

One may anticipate various barriers that include the following: The ability to translated/formulated diverse quantitative findings and products into consistent and compatible measures to allow integration; The accommodation of nonrisk attributes that are important for decision-makers in a broader, multiattribute context; Addressing stake-holder concerns and their constraints and incorporating these concerns into test beds and Center products; Gaining a committed acceptance by stakeholders, so that ultimately the enabling Center technologies will spawn new, retrofit infrastructure designs and more-encompassing and effective protective systems and measures in the future; Extending the decision-analysis methods from a single structure to groups of structures. Therefore, one can envision various projects in this area:

- Multiattribute Decision-Analysis
- Catalog of Databases and Software Tools

- Extension and Combination of Databases and Software
- Combination and Interaction of Multiple Models and
- Test-bed Application of Tools

8. Technology Transfer, Education, and Training

The goal of the strategic education plan is to empower a broad spectrum of key segments in society (students, technical and nontechnical staff, policy makers, etc.) who have the skills to develop technical and policy solutions for multihazard engineering at the local, national, and global scale. This vision involves the development of an educational and training program that will combine communication skills, cultural awareness, innovation, technical knowledge, and understanding of societal impacts. This vision should be addressed through a multilevel education programs including integrated coursework, exchange programs with partner institutions, and assessment activities.

9. Summary

Current approaches to overcome the effects of single hazards are insufficient for protecting Society from likely abnormal multihazard events. The risk to Society from such incidents increases with the increases in population densities, and the localization of critical infrastructure systems. Overcoming this monumental challenge might require resources that exceed the abilities in a single nation. Therefore, Society must develop, collaboratively, capabilities to address and mitigate multihazard incidents within a multinational framework. This paper provides background on a possible multihazard research approach for protecting critical urban infrastructure systems. This effort is vital for the development of more effective solutions to problems that are currently addressed primarily with conservative, and/or empirical approaches. The expected outcome will have a profound effect on national and international peace, prosperity, and security. Essential work must be conducted in several important areas that include scientific and technical issues, as well as socio-economics and public policy.

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THE ROLE OF SPATIAL PLANNING IN STRENGTHENING URBAN RESILIENCE

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Abstract: This article explores the challenges for dealing with risks from a spatial planning perspective. It points at the role spatial planning can play in mitigating multihazards by influencing urban structures and thus strengthening urban resilience. However, it also shows the limits of spatial planning and calls for an integrated approach including a variety of authorities to dealing with multihazards.

Keywords: spatial planning; natural hazards; technological hazards; vulnerability; urban resilience

1. Introduction

Disasters like earthquakes, coastal and river floods or nuclear power plant accidents show that physical structures and—more generally—regional development may be severely threatened by natural and technological hazards. The resulting "traditional" natural and technological risks more and more become intertwined with the group of so-called "new emerging risks" such as genetic engineering, nanotechnology as well as the group of risks due to intentional action such as wars and terrorism. The reason for this increasing intertwinement is the growing

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complexity and global integration of economical, social and physical structures thus leading to an increasing vulnerability, especially in urban areas.

This chapter explores these new challenges in dealing with risks from a spatial planning perspective. It points at the role spatial planning can play in mitigating multihazards by influencing urban structures. Due to the character of spatial planning, the article concentrates on those actions that help to strengthen urban resilience before an event happens. This has to be distinguished from other authors that focus more on the question how, e.g., cities can recover after a disastrous event has happened (e.g., Vale and Campanella, 2005).

However, the article also shows the limits of spatial planning and calls for an integrated approach including a variety of authorities to dealing with multihazards.

The hypothesis of this article is that spatial planning plays an important role in influencing urban structures in a way that cities are made less vulnerable to multihazard threats. The question, however, is what can be understood as the urban structure?

In this article, urban structure is understood in a threefold way:

1. *Physical/environmental structure:* Physical elements of the urban environment such as the settlement structure (buildings, infrastructure) or the communication network as well as elements like the network of green spaces (parks, rivers, etc.).
2. *Socioeconomic structure:* Distribution of social groups, distribution of income, degree of economic and social coherence, etc.
3. *Institutional structure:* Hierarchy of institutions, legitimation of institutional decisions, trust in institutions by the public, quantity and quality of the institutions' personnel, degree of responsibility, degree of cooperation and coordination among institutions.

2. Urban Resilience and Urban Vulnerability

2.1. RISK AS THE INTERACTION OF HAZARDS AND VULNERABILITY

In recent scientific literature, disasters are defined as the result of an interaction between two variables: hazards (e.g., triggering agents stemming from nature, as well as from human activity) and vulnerability (e.g.,

susceptibility to injury or loss influenced by physical, social, economic and cultural factors) (e.g., McEntire, 2001; Henstra *et al*., 2004).

In this context, it should be emphasized that a universally valid definition of these terms does not exist and that definitions vary largely (e.g., summarized by Thywissen, 2006). However, it is more important to find a common understanding in terms of a knowledge base rather than a common definition.

A *hazard* can be defined as "any potential threat to something that people value, including one's life, health, environment or lifestyle" (Mills *et al*., 2001). Hazards are often distinguished between natural and man-made or technological hazards.

For *vulnerability*, several definitions can be found in literature (Cutter, 1996, p. 531). When referring to vulnerability it is important to distinguish between the origins of vulnerability: In general, vulnerability is defined as a potential for loss but in most cases it is not clearly defined what type of loss and whose loss is meant. The following types of losses—and therefore origins of vulnerability—can be distinguished (Cutter, 1996, p. 530):

- Individual potential for and sensitivity to losses, occurring in spatial and nonspatial domains (*individual vulnerability*).
- Susceptibility of social groups or the society at large to potential structural and nonstructural losses from hazardous events and disasters, occurring in distinct spatial outcomes or patterns and variation over time (*social vulnerability*).
- Potential for loss derived from the interaction of society with biophysical conditions that affect the resilience of the environment to respond to the hazard or disaster. They also influence the adaptation of society to such changing conditions, occurring also in explicit spatial outcomes (*biophysical vulnerability*).

Apart from the origin based categorization, vulnerability can be found in relation to three distinct themes in research (Cutter, 1996, p. 530f.):

Vulnerability as risk/hazard exposure examines the source (or potential exposure to risk) of biophysical or technological hazards and focuses on the distribution of hazardous conditions and human occupancy of hazardous zones in combination with the occurrence of a hazardous event (e.g., Hewitt and Burton, 1971).

Vulnerability as social response focuses on coping responses including societal resistance and resilience to hazards. The nature of the hazardous event is usually taken as a given—or at the very minimum viewed as a social construct—but not a biophysical condition. Here, the social construction of vulnerability is highlighted, rooted in historical, cultural, social and economic processes (e.g., Chambers, 1989; Bohle *et al.*, 1994; Blaikie *et al.*, 1994).

Vulnerability of places focuses on the combination of the elements of the first two directions but is more geographically centered, being "both a biophysical risk as well as a social response, but within a specific areal or geographic domain" (Cutter, 1996, p. 533).

The vulnerability of places approach is most likely the concept that will be used in the context of this article because on the one hand the physical existence of hazards cannot be denied. On the other hand, and as it will be shown later, risks depend very much on societal aspects like perception of risks, cultural or economic aspects.

2.2. RESILIENCE

Resilience is a term that has been used in a variety of contexts. Henstra *et al*. (2004) show that resilience has been defined in different ways since the 1970s. They suggest the following definition in the context of disaster resilient cities: Resilience thus is "the capacity to adapt to stress from hazards and the ability to recover quickly from their impacts (Henstra *et al*., 2004, p. 5).

According to Godschalk (2002), general hazard mitigation guidelines do not sufficiently accommodate the particular vulnerabilities of "cities under stress". Thus, "urban hazard mitigation" that aims at the development of resilient cities shall be emphasized. He characterizes resilient cities as follows:

> "Such cities are capable of withstanding severe shock without either immediate chaos or permanent deformation or rupture. Designed in advance to anticipate, whether, and recover from the impacts of natural or technological hazards, resilient cities are based on principles derived from past experience with disasters in urban areas. While they may bend from hazard forces, they do not break" (Godschalk, 2002, p. 2).

In order to create disaster resilient cities, Godschalk derives characteristics—or principles—of resilient systems that shall be taken into account for the design and management of cities (Godschalk, 2002, p. 5):

- *Redundancy:* systems designed with multiple nodes to ensure that failure of one component does not cause the entire system to fail
- *Diversity:* multiple components or nodes versus a central node, to protect against a site-specific threat;
- *Efficiency:* positive ratio of energy supplied to energy delivered by a dynamic system;
- *Autonomy:* capability to operate independent of outside control;
- *Strength:* power to resist a hazard force or attack;
- *Interdependence:* integrated system components to support each other;
- *Adaptability:* capacity to learn from experience and the flexibility to change;
- *Collaboration:* multiple opportunities and incentives for broad stakeholder participation.

According to Godschalk's model, resilience is a way to cope with uncertainty due to the fact that the frequency and magnitude of hazard agents can be rarely predicted, and because the vulnerability of community systems cannot be fully known before a hazard event. Thus, cities must be designed with the strength to resist hazards, the flexibility to accommodate extremes without failure and the robustness to rebound quickly from disaster impacts (Henstra *et al*., 2004, p. 8).

3. Spatial Planning at the Urban Level

Spatial planning is often used as a synonym for urban planning—which is not quite correct. This misunderstanding is caused by the different understandings of the terms in different countries (and of course its translation to English). The variety encompasses terms like "land-use planning" (e.g., Ireland), "land planning" (Italy), "spatial planning" (Germany: *Raumordnung*), "town and country planning" (UK), others use "spatial development" (Poland: *Zagospodarowanie przestrzenne*), "regional development planning" (France: *aménagement du territoire*), etc.

The meaning of these terms has evolved in the particular legal, socioeconomic, political and cultural conditions of the country or region in question. So, the terms are not transferable to other countries, except in the most general sense; even if the same words are used; e.g., *aménagement du territoire* has a different meaning in Belgium, France and Luxembourg. So the use as well as understanding of "spatial planning" is wide open. That is the reason why it is important to make clear "definitions" for a better understanding and avoidance of mistakes.

Spatial planning is in this article defined as the comprehensive, coordinating spatially-oriented planning at all spatial scales—from the national down to the community level—seeking to influence the future distribution and pattern of activities in terms of their locations. Spatial planning operates on the presumption that the conscious integration of (particularly public) investment in sectors such as transport, housing, water management, etc. is likely to be more efficient and effective than uncoordinated programmes in the different sectors (adapted from ODPM, 2005).

Throughout different countries, two main levels of spatial planning can be distinguished (Fleischhauer, 2006a, p. 12):

1. *Regional planning:* Regional planning is the task of settling the spatial or physical structure and development by drawing up regional plans as an integrated part of a formalized planning system of a state. Regional planning is required to specify the aims of spatial planning, at an upper, overarching level. The regional level represents the vital link between a state-wide perspective on development and the specific decisions on land uses taken at a local level within the municipality's land-use planning. Its textual and cartographic determinations and information normally range in the scales of 1:50,000 to 1:100,000.

2. *Local land-use planning:* Local land-use planning is the creation of policies at a local/municipal level that guide the land and resource use inside the administrative borders of the municipality in charge of this task. Sometimes, "urban planning" is used as a synonym. The main instrument of land-use planning is zoning or zoning ordinances, respectively. Land-use planning is situated below the regional planning level and consists normally of two stages: First, a general or preparatory land-use plan (scale 1:5,000–1:50,000)

for the whole municipality and second a detailed land-use plan for a small part of it, mostly legally binding (scale 1:500–1:5,000).

In contrast to the broad, comprehensive character of spatial planning, several sectoral planning authorities are in charge of single spatially relevant topics (e.g., water management, landscape planning, transport planning, etc.). Although not encompassed by the narrow definition of spatial planning, such sectoral plans often have effects on the spatial structure and thus are called *spatially relevant plans*.

TABLE 1. Overview of spatially (non-)relevant planning and management (Own table)

Spatial level	Spatially relevant planning				Spatially nonrelevant planning
		Comprehensive (use and development of land)		Sectoral (transport, water, geology, emergency response, etc.)	Forms of nonspatial management on different spatial levels
Europe		European spatial development (ESDP, Territorial Agenda; no binding character)		Environmental Policies, TEN, CAP	e.g., budget planning
Member State	Spatial planning	Spatial development planning	Sectoral planning	e.g., national transport network plan	e.g., defense planning, education
Submember State level (federal state, region, or other spatial units)		Regional planning		e.g., river basin authorities in charge of management plans	e.g., cultural development, education planning
Municipality (all planning at this level can be subsumed together under the term *"urban planning and management"*)		Land-use planning		e.g., waste, sewage planning, public transport planning	e.g., lower education, municipal budget planning

Apart from spatially relevant planning, also other planning exists that is not at all spatially relevant. All spatially relevant and nonrelevant planning activities at the urban level can be subsumed under the term "urban planning and management". Thus, urban planning is much broader defined than local land-use planning. Its broad definition can be seen as an outflow of the comprehensive competences municipalities have in the whole world but in particular in Europe.

4. Role of Spatial Planning in Hazard Mitigation: Theoretical Reflections

4.1. SPATIAL RELEVANCE OF NATURAL AND TECHNOLOGICAL HAZARDS

The spatial character of a risk is defined by spatial effects that might occur if a hazard turns into a disaster. Of course, every hazard has a spatial dimension (disasters take place somewhere). But the occurrence of spatially relevant hazards (Table 2) is limited to a certain disaster area, which is regularly or irregularly prone to hazards (e.g., river flooding, storm surges, volcanic eruptions). Spatially nonrelevant hazards occur more or less anywhere. For example, murder, drug abuse or road accidents definitely belong to the main risks in Western societies. However, risks like these do not have any specific spatial relation, which means that their occurrence is not limited to some exclusive areas.

Table 2 shows that not all hazards lead to spatially relevant risks. Hazards like volcanic eruptions, river floods, storm surges, tsunamis, avalanches, landslides, hazards from nuclear power plants or major accident hazards have the highest spatial relevance. Other hazards, such as terrorism, have a medium spatial relevance because they might occur in only certain areas (city centers, transport nodes, etc.). However, such areas are large in number and often broadly spread over the territory. Thus they are ubiquitous to a certain extent.

It has to be acknowledged, however, that, e.g., terrorism can trigger hazards that are spatially highly relevant. This points at the need to look at hazards not only from a one-dimensional or sectoral but from a multidimensional perspective. This will be explored from a spatial planning perspective in the following part.

TABLE 2. Spatial planning relevance of risks (Adapted from Fleischhauer, 2006b, p. 13)

Risks/hazards	Spatial filter Specific spatial relevance: ++ = high, + = low, 0 = none
Volcanic eruptions	++
River floods	++
Storm surges	++
Tsunamis	++
Avalanches	++
Landslides	++
Hazards from nuclear power plants	++
Major accident hazards	++
Earthquakes	+
Droughts	+
Forest fires	+
Winter and tropical storms	+
Extreme temperatures (heat waves, cold waves)	+
Hazards from oil processing, transport and storage	+
Air traffic hazards	+
Terrorism, war, crime	+
Instability of the West Antarctic ice sheet	+
Hazards along transport networks	+
Long-term consequences of human-induced climate change	+
Destabilization of terrestrial ecosystems due to human induced change of biogeochemical cycles	+
Electromagnetic fields	+
Hazards from the collapse of thermohaline circulation (breakdown of the North Atlantic Stream)	0
Nuclear early warning systems and nuclear, biological and chemical weapons systems	0
Epidemics (e.g., AIDS infection)	0
Carcinogenic substances in low doses	0
Mass development of anthropogenically influenced species	0
Meteorite impacts	0
Self-reinforcing global warming (runaway greenhouse effect)	0
Release and putting into circulation of transgenic plants	0
BSE/nv-CJD infection	0
Certain genetic engineering interventions	0
Dispersal of persistent organic pollutants (POPs)	0
Endocrine disruptors	0

4.2. SPATIAL PLANNING AND MULTIHAZARDS

Regarding risk management and the role of spatial planning, an interesting shift can be observed which especially relates to the demands that are made on spatial planning. Until the mid-1990s, natural hazards were mainly addressed by concepts of emergency management units or other sectoral planning divisions. It is due to authors like Burby (1998) or Godschalk *et al*. (1999) who highlighted the need and the important role spatial planning has to play in the whole risk management cycle. In recent years, however, this has not only been accepted by planners and policy makers. It corresponds also with latest research initiatives where the potential role of spatial planning in risk assessment and management has been stressed (e.g., European Commission, 2003).

Spatial planning decisions have to consider all spatially relevant sectoral hazards. Spatial planners cannot reduce their focus on only one or two hazards like floods or potentially dangerous industrial facilities. The reason is that spatial planning is responsible for a particular spatial area (where the sum of hazards and vulnerabilities defines the overall spatial risk) and not for a particular object (like, e.g., sectoral engineering sciences). Therefore spatial planning must adopt a multihazard approach in order to deal appropriately with risks and hazards in a spatial context.

Integrative approaches for assessing hazards in their spatial context (‘hazards of place’) have been developed by geographers since the 1970s (Hewitt and Burton, 1971, Cutter and Solecki, 1989). However, further methodological elaborations on this subject have rarely been attempted, as Cutter (1996) points out. Nevertheless, the ‘hazards of place’ approach is meanwhile well established in the field of geography. In contrast, a multihazard approach has not been addressed by the discipline of spatial planning for many years, especially in Europe. Although there is a tradition of spatial planning research for single hazards (coastal flooding, river flooding, earthquakes, nuclear power plants), an integrated research approach to spatially relevant hazards has only recently been undertaken by a few authors (Egli, 1996; Burby, 1998; Godschalk *et al*., 1999; Greiving, 2002; Schmidt-Thomé, 2006).

In this context it is noteworthy that several risk assessment methodologies have recently been extended from a single to a multihazard approach (e.g., UNDP Disaster Risk Index, see UNDP, 2004, or HAZUS MH, see FEMA, 2005). A main reason for this recent change of

perception is the realization that risk potentials are increasing and that it is not sufficient to restrict risk policies only to the response phase of the emergency management cycle. Rather, in order to promote a sustainable development, it is an indispensable prerequisite to mitigate hazards—a task where spatial planning can play an important role.

4.3. ROLE OF SPATIAL PLANNING IN RISK MANAGEMENT

Risk management can be interpreted as an ongoing process and is often illustrated by the so called disaster management cycle by which public and private stakeholders plan for and reduce the impact of disasters in the preemergency phase (prevention and preparedness), react in the emergency phase (response) and in the postemergency phase (recovery) (Figure 1).

The integration of the elements of risk assessment (assessment of hazards, vulnerability and risk as such) and risk communication (communication of risk assessment and risk management activities) into the disaster management cycle (or the phases of risk management) results in a "risk governance cycle" which emphasises the ongoing character of risk governance. At all points of the cycle, appropriate actions can

Figure 1. Integration of risk governance into the disaster management cycle—"risk governance cycle". (Own figure.)

result in a reduction of hazard potential or vulnerability. According to the risk management cycle, the reductionof vulnerability can be achieved by improving the prevention and preparedness of a region or a society. Such improvement measures, however, have to be based on a reliable assessment of risk (and/or its elements "hazard" and "vulnerability") and have to be complemented and supported by an appropriate risk communication process.

Spatial planning plays an important role, especially in the area of prevention by helping to reduce the vulnerability of societies to natural hazards. However, it is also visible that spatial planning is only one of many actors in the field of risk management.

5. Role of Spatial Planning in Hazard Mitigation: The View at Planning Practice

5.1. FINDINGS FROM THE ARMONIA PROJECT

The following findings are a result of an assessment of spatial planning approaches to natural hazards in eight EU Member States country studies that were initiated by the ARMONIA project[1] and originally carried out following a common structure which enabled a comparative evaluation of the case studies and the identification of advantages and problems of the different planning systems and the practices of dealing with natural hazards (Fleischhauer *et al.*, 2006). The questions that had to be answered in the country studies went into two directions: First it was asked how spatial planning considers natural hazards and second how the assessment and management of natural hazards are organized and if spatial planning plays a decisive role herewith. Table 3 gives an overview of the central findings.

5.1.1. *Assessment Results*

At a very general level (without distinguishing between planning levels and single hazards) the table shows that most natural hazards

[1]ARMONIA—Applied Multi-Risk Mapping of Natural Hazards for Impact Assessment. European Commission, Sixth Framework Programme for Research and Technological Development, Thematic Area "Global Change and Ecosystems," 2004–2007.

TABLE 3. Overview of basic information in dealing with natural hazards (Wanczura, 2006, p. 176)

Country	Hazards dealt with in spatial planning	Authority in charge of		Use of maps in planning practice		Used vulnerability indicators	Multirisk aspect considered?
		Risk assessment	Risk management	Hazard maps	Risk maps		
Finland	FL, LS, FF, EQ, EE	SEP	SEP, SPP	+	0	PD	0
France	LS, FL, FF, EQ	SEP	SEP, SPP	++	+	PD	++
Germany	FL, LS, EE, LS	SEP	SEP, SPP	++	+	DP	0
Greece	FL, FF, VO, EQ	SEP	SEP, SPP	+	+	No data	0
Italy	FL, LS, VO, FF	SEP	SEP, SPP	+	+	No data	+
Poland	LS, FL, FF, EQ	SEP	SEP, SPP	+	+	DP, PD, OI	0
Spain	FL, LS, FF, VO, EQ	SEP	SEP, SPP	++	+	PD, OI	0
U.K.	LS, FL	SEP	SEP, SPP	+	+	No data	0

LS = Landslides
FL = Floods
FF = Forest Fires
VO = Volcanic hazards
EQ = Earthquakes
EE = Extreme meteorological events

SEP = sectoral planning
SPP = spatial planning

++ = high importance/yes
+ = medium importance/partly
0 = low/no importance/no

DP = economic damage potential
PD = population density
OI = other indicators

(landslides, floods, forest fires, volcanoes and earthquakes) are addressed by spatial planning. On the other hand, natural hazards are not taken into account by spatial planning in every case. Here, significant differrences exist between the different countries.

On the other hand, the studies have revealed some surprising similarities between the assessed countries concerning the responsibility of risk assessment and risk management. In all countries, only sectoral

planning divisions are responsible for the assessment of risks. Spatial planning plays no significant role in this context.

Further, risk management is mainly based on hazard related information while no attention is paid to the given hazard exposure (Germany, Finland and Spain). Only in France the use of hazard and risk maps for all relevant hazards seems to be common. The analysis revealed that in planning practice the use of hazard maps is made only in a few countries (France, Spain) whereas risk maps are not in use at all. This corresponds with the fact that there is a dominance of hazard assessment in the assessed Member States. Similarly, only little attention is paid to vulnerability, i.e., the use of vulnerability indicators or vulnerability maps (as, e.g., seen in the example of Germany).

The responsibility for risk management is shared by sectoral planning and spatial planning whereas spatial planning plays only a minor role and mainly acts in the area of hazard mitigation due to the long-term character of planning decisions. At the regional level, various responsible sectoral planning divisions are in charge of the management of natural risks. Regional planning is often only *one of many* supporting actors with the duty to implement measures, or to secure the implementation of measures which are carried out by sectoral planning divisions. Only in the context of nonstructural mitigation measures is spatial planning important for the minimization of damage potential (Finland and Germany). In contrast, municipalities which are a major actor at the local level use land-use planning as only one of many other tools to reduce the risks within their area of responsibility (Germany, France and Poland).

A further question in the focus of the analysis was, if multihazard approaches for assessing natural risks exist and if they were taken into account in planning practice. This was assumed to be of importance as a spatial view of natural hazards should consider *all* kinds of hazards through a multihazard or multirisk approach at all spatial levels. Spatial planning cannot reduce its focus on only one or two hazards because it is responsible for a particular spatial area and not for a particular object. In contrast to the theoretical ideal, most risk assessment approaches analyzed in the different Member States have a single hazard focus and/or a project oriented perspective. In some cases they are based on scientific studies without any significant influence on planning practice (Germany). In the analyzed countries the only examples of a multirisk approach systematically introduced as an analytic basis for planning practice have been found in France, Greece and also Italy.

Above these findings, an additional observation in all assessed countries was that the intensity of attention paid to natural hazards depends on the experiences from *recent* disastrous events rather than the occurrence of disastrous events in the more distant past or scientific hazard assessments (disaster driven process). Consequently, risk assessment and management focus on more frequent hazards than on less frequent events. The result is a tendency to underestimate the hazard and risk presented by extreme events.

Further, in all of the analyzed best practice examples, special attention is paid to the coordination of the activities of all involved actors in the whole disaster driven process, i.e., mitigation, preparedness, response and recovery. The general planning practice, however, is characterized by actors who operate without or with only a few coordination among each other.

A basic requirement for any kind of risk assessment to be used in spatial planning is the existence of and a legally binding basis for hazard and risk maps. This means, spatial planning needs specific spatially and cartographically presentable information as a basis for decisions about future land-use as well as land development. It is necessary that this information has to fit with the spatial scale to be used at regional or local level. The analyzed planning practice indicates that hazard mapping is an obligatory task in most assessed countries, at least for the most relevant hazard of river floods (Germany and United Kingdom). Only in some analyzed countries the existing legal basis for hazard and risk maps is actually neither sufficient nor satis-factory (e.g., in Poland where until present no legal framework exists at all).

5.1.2. *Assessment Conclusions*

From the assessment, the following conclusion can be drawn: Spatial planning is not responsible for undertaking risk assessment, but makes use of the results provided by sectoral planning. However, the relevance of risk assessment for spatial planning has to be readjusted again: Spatial planning normally needs only hazard information; risk and vulnerability are only important in a few extreme situations (e.g., where relocation of existing development is being considered). For risk management (nonstructural mitigation activities), only the vulnerability of the different objects to be protected is, in general, of relevance (e.g., the different type of land-uses or the different types of

buildings). In contrast, structural mitigation and emergency planning need information about the existing vulnerability. This information has to be seen as a basis for the analysis of costs and benefits of given alternatives or evacuation plans.

5.2. CASE STUDY OF THE 2002 DRESDEN FLOOD EVENT

An extreme event turns into a disaster when levels of damage are reached that exceed the capabilities and standards of the management system (i.e., mitigation, preparedness measures, design of technical works, emergency management, etc.). These levels can be exceeded on the event side (or in predisaster terms the hazard side) and/or on the damage side (ex-ante expressed by a region's vulnerability). The analysis of the Elbe flood in the Dresden region shows that both aspects had their share: the extreme magnitude of the event as well as the regional vulnerability.

5.2.1. *Severity of the Event*

The large quantities of rain between 11 and 14 August 2002 caused a massive discharge of water that inevitably had to lead to floodings. However, the extreme event that would have caused massive destructtions in any case was increased by several factors.

The main increasing factor was the reduced water runoff potential once the water had begun to raise. This reduced runoff potential lead to a peak gauge of 9.40 m. It was a result of an accumulation of the effects of aggradations on the river banks, natural cover and buildings in the flooding areas that have been constructed in the last decades. A famous example is the Dresden ice hockey and skating stadium that was built in 1969 amidst the flood protection area (Jakob, 2005).

In the case of the Elbe flood in Dresden, certain settings of *vulnerability* caused that the flood event turned into a disaster. These settings can be found in all stages of the disaster management cycle.

5.2.2. *Gaps in Disaster Prevention*

Although preventive flood protection has always played an important role in the city's policies, one had to observe some *gaps in the field of*

disaster prevention. A main reason for the severe damages was the *accumulation of damage potential* in flood hazard zones. Especially after German unification, the aim of improving the economic situation of the city of Dresden and the dynamics of the development set pressure on many of the city's areas that were prone to flood hazards. Political pressure and a decreasing flood risk perception caused that housing and commercial areas were designated in flood prone areas (Korndörfer, 2001). A recent example was the construction of the new congress centre nearby the river banks.

The accumulation of damage potential was mainly aggravated by the existence of dikes because they lead to a false feeling of safety. As a consequence, many residential areas that have been built up in the last decades are situated in areas that are in danger of being flooded in case of a dike collapse. During the 2002 Elbe flood, indeed many of the dikes—that have been constructed since the 12th century—turned out to be unsafe. In Saxony 131 dike collapses or overflows were reported (DKKV, 2003, p. 81). The resulting damages often were even higher due to the high velocity and the short warning time.

The flood event of 2002 has also shown aspects of *institutional vulnerability* within disaster prevention that is mainly characterized by a lack of cooperation. Traditionally, the German federal states have a strong position and therefore also follow their own interests concerning flood protection. Some successful examples of cross-state cooperation in river basins (Oder, Rhine and Elbe) shall not belie the fact that such cooperations are still an exception. Main problems in this respect are a nonexistent balance between upstream and downstream riparians and not coordinated strategies for producing flood maps and flood protection concepts (DKKV, 2003, p. 41).

A third aspect of drawbacks in the area of prevention was the fact that many people that were hit by the disaster were *not insured* against flooding. In the affected areas in Saxony and Saxony-Anhalt, 50% of those households who were hit by the flood had a coverage of the damages by an insurance (DKKV, 2003, p. 62). Compared to other flood threatened regions in Germany, this is a quite high percentage—compared to the severity of the event, however, it shows how many households had to rely on state compensations.

5.2.3. *Low Preparedness*

The *low preparedness* of authorities and the public also lead to an increase of damages. During the last decades the flood risk awareness had been disappearing because of some technical flood protection measures that have been constructed upstream (especially barrages in the Czech Republic) but mainly due to the missing experiences with previous flood events. Consequently, about 40–50% of the people did not know how to prepare for a possible flood event (DKKV, 2003, p. 56).

5.2.4. *Inefficient Response*

Just before a disaster strikes, it is a question of appropriate response of authorities (weather and flood warnings, emergency response) and the citizens to reduce potential damages as much as possible. Also in this area of the disaster management cycle, *inefficient response* has to be reported.

A main problem was a lack of appropriate information in the pre-disaster phase, namely in the area of weather warnings and flood forecast. For example, the weather warnings of the German Meteorological Service (Deutscher Wetterdienst, DWD) did not reach the emergency response authorities in time and did not have a sufficient spatial resolution in order to derive explicit emergency response measures (DKKV, 2003, p. 87). Further, the system of flood forecast which can normally forecast water levels 1–5 days in advance did not supply the exact information. The main problem was that the existing flood forecast models for the Elbe river could not be fed with appropriate input data of the water level-discharge relation because of the extreme water levels that have never been reached before (DKKV, 2003, p. 6).

Finally, the information flow between institutions as well as between public authorities and the population showed some significant weaknesses that worsened the situation in the event phase:

Low coordination between flood warning and emergency response authorities: The Elbe flood showed a bad feedback of the districts—which are responsible for emergency planning and response—with the flood warning and forecast authorities. One example was that the official flood warning from the State of Saxony Environmental and Geological Office (*Landesamt für Umwelt und Geologie*,

LfUG) was made almost two hours after disaster alarm was triggered off in some of the districts[2] e.g., the *Weißeritzkreis* (Kirchbach *et al*., 2002, p. 85ff.). This low coordination of activities happened due to the fact that emergency response in Germany is located at a decentral local level. The duty of triggering off disaster alarms and coordinating first emergency response activities lies in the responsibility of the districts.

Inconsistent information: In some cases (e.g., *Mulde* river basin), inconsistent information about the expected water gauges in the same river basin was given due to the fact that within the same river basin different territorial authorities were responsible for generating and forwarding flood warnings.

Delayed and/or imprecise information: The information of the population during the Elbe flood in many cases happened too late or even not at all. More than 40% of the affected people stated that they had not been warned at all (DKKV, 2003, p. 97). Those who received a warning often found this too imprecise in order to take appropriate measures against the flood, be it that the warnings did not contain any advice how to act or that the warning was made without any spatial specification (DKKV, 2003, p. 97).

Another problem was the lack of cooperation between the actors of emergency response. Due to the traditionally decentralized and federal structures in Germany, emergency response cannot be seen as an entire institution but a set of organizations and institutions that act at different levels and with different competences. Emergency management is legally fixed by federal state laws and it encompasses state authorities as well as non governmental organizations. Although the coordination of emergency response activities is under responsibility of the districts, the splitting of competences and the low practice of cooperation lead to inefficiencies that became obvious during the Elbe river flood (DKKV, 2003, p. 115ff.):

Lack of cooperation between emergency management actors: Here, a lack of experience in working together has to be mentioned as well

[2] Districts (*Kreise*) are the administrative level above the municipal level. In general they consist of several municipalities. Large cities (like Dresden) often do not belong to a district and are therefore independent urban districts. In the Dresden region the districts *Weißeritzkreis*, *Kreis Sächsische Schweiz*, *Kreis Meißen* and the district-free City of Dresden vary between 328 km² and 890 km² in size and 122,000 and 490,000 in population.

as a lack of communication and willingness to cooperate with each other.

Main focus on own organization: Many emergency management organizations are focused on themselves and are not informed about the capacities of other organizations. This leads to large inefficiencies because some qualifications and equipment are provided in parallel while others are missing.

Internal weaknesses: Further, internal weaknesses of each organization like the lack of knowledge, missing motivation or discipline as well as a weak leadership were responsible for inefficiencies in emergency response.

The findings from this analysis can be summarized in the following matrix that relates the elements of vulnerability to the phases of the disaster management cycle (Table 4).

The Elbe flood has lead to a number of general legal changes and single improvements of territorial (spatial planning related) and

TABLE 4. Relation of vulnerability and disaster management in the 2002 Elbe river flood (Own table)

Disaster management cycle phase / Element of vulnerability	Prevention	Preparedness	Response
Damage potential (physical)	Accumulation of damage potential in flood hazard zones	No experience how to use/interpret hazard information	Inconsistent/delayed information about hazards
Safe/unsafe conditions (individual, social and institutional coping capacity)	Lack of cooperation of authorities (institutional)	Lack of insurance coverage (individual) Lack of hazard awareness (individual, social, institutional)	Lack of cooperation between actors of emergency management (institutional) Lack of coordination of hazard assessment and risk management (institutional) Lack of appropriate information

structural (building related) prevention as well as disaster preparedness (insurance, hazard information system, institutional changes). Among these changes especially the institutional changes can be considered important as they have led to a more integrated organizational structure to address not only river flooding but also natural and technological hazards in general.

These examples have shown that theory and practice of dealing with natural hazards diverge quite largely from each other. The following chapter points at some important aspects to close the gap.

6. Urban Resilience: The Role of Spatial Planning

Spatial planning action is especially important in the area of prevention which aims at a reduction of damages to people, property, and resources before a disaster strikes. The goal of disaster preparedness is to reduce vulnerability and the hazard potential. It refers to actions that have a long-term impact (e.g., spatial planning as nonstructural mitigation activities but also structural mitigation like reinforcement of protection infrastructure or buildings). The role of spatial planning in principle includes the following actions of territorial prevention which can be taken at different levels of planning (regional, local) to reduce vulnerability (especially damage potential) and hazard potential:

Keeping areas free of development: Spatial planning has the instruments at hand to keep areas of land free of future development that are (a) prone to hazards (e.g., flood-prone areas, avalanche-prone areas), (b) that are needed to lower the effects of a hazardous event (e.g., water retention areas) and (c) that are needed to guarantee the effectiveness of response activities (e.g., escape lanes and gathering points).

Differentiated decisions on land-use: Apart from keeping certain areas free of development, spatial planning may also decide on acceptable land-use types according to the intensity and frequency of the existing hazard (e.g., agricultural use of a moderately hazardous flood area might be allowed whereas residential use may be forbidden).

Recommendations in legally binding land-use or zoning plans: Although recommendations about certain construction requirements belong to the area of building permissions, some recommendations

may be made at the level of land-use or zoning plans (e.g., minimum elevation height of buildings above floor, prohibition of basements, prohibition of oil heating, type of roof).

Influence on hazard intensity and frequency (= hazard potential) by spatial planning: Spatial planning can also contribute to a reduction of the hazard potential, e.g., protection or extent of flood retention areas, protective forest, etc.

Table 5 lists principles that a system shall fulfill in order to be resilient to threats. These principles follow the definition of Godschalk (2002). The table then shows with some examples to which principles of a resilient regional or urban system spatial planning and other spatially relevant planning (sectoral planning) can contribute. In those cases where neither spatial planning nor sectoral planning seem to play an important role, also supporting instruments are mentioned.

Table 5 shows that spatial planning can mainly contribute to the resiliency principles of redundancy, diversity and strength and to a lower degree to the principle of collaboration.

The reason for this quite restricted role of spatial planning is that the core task of spatial planning is the organization of land-use and the reduction of land-use conflicts. Thus, spatial planning can contribute to all those principles of urban resilience that are connected with the physical/environmental urban structure. For the socioeconomic and institutional structure, spatial planning only plays a role in connection with other political and administrative authorities.

Further, there is another limitation: Spatial planning can only significantly influence spatial structures during the planning and decision-making process, e.g., for new residential areas or transport networks. Once an area is built-up, however, spatial planning hardly can contribute to any changes any more. To improve, e.g., the resilience of built-up areas is a task for sectoral planning or other urban planning and management actions.

Finally, due to the medium and long-term character of spatial plans and the persistence of spatial structures, spatial planning can not at all react spontaneously to nonspatial but at the same time sudden threats or impacts like terrorist attacks. However, spatial planning may nevertheless contribute in advance to reduce the severity of effects in case of such an event.

TABLE 5. Examples for the contribution of spatially relevant planning and supporting instruments to urban resilience (Own table).

Principles of urban resilience	Regional planning	Local land-use planning	Sectoral planning	Supporting instruments
Redundancy	Polycentric settlement structure (designations in regional plans)	Reduction of high urban densities; physical structure with multiple nodes (zoning instruments)	Physical structure with multiple nodes (energy supply, road network, rail network, etc.)	—
Diversity	Polycentric settlement structure (designations in regional plans)	Reduction of high urban densities; physical structure with multiple nodes (zoning instruments)	Physical structure with multiple nodes (energy supply, road network, rail network, etc.)	—
Efficiency	—	—	—	Cooperation of institutions; making use of comparative advantages
Autonomy	—	—	—	Responsibility, legitimation of institutions
Strength	Maintenance of protective features of the natural environment that absorb or reduce hazard impacts; secure the availability of space for protective infrastructure	Structural prevention measures as a part of building permissions; secure the availability of space for protective infrastructure	Construction and maintenance of protective infrastructure	—

(Continued)

TABLE 5. *(Continued)*

Principles of urban resilience	Regional planning	Local land-use planning	Sectoral planning	Supporting instruments
Interdependence	—	—	—	Cooperation of institutions; information management
Adaptability	—	—	—	Information management; governance principles
Collaboration	Interregional cooperation	—	—	Cooperation of institutions; information management

7. Summary and Conclusion

This article has shown that spatial planning plays an important—but only one of many—role for creating resilient urban structures. Although from a theoretical point of view, the role of spatial planning can be seen as well defined, the look at planning practice reveals that there are many shortcomings concerning spatial planning but also concerning disaster mitigation for resilient cities in general.

To create resilient urban structures, there is a need for a close cooperation between spatial and sectoral planning authorities, as well as between administrative and political authorities. This cooperation shall ideally include an agreement on disaster resilience objectives, information management but also the involvement of the public.

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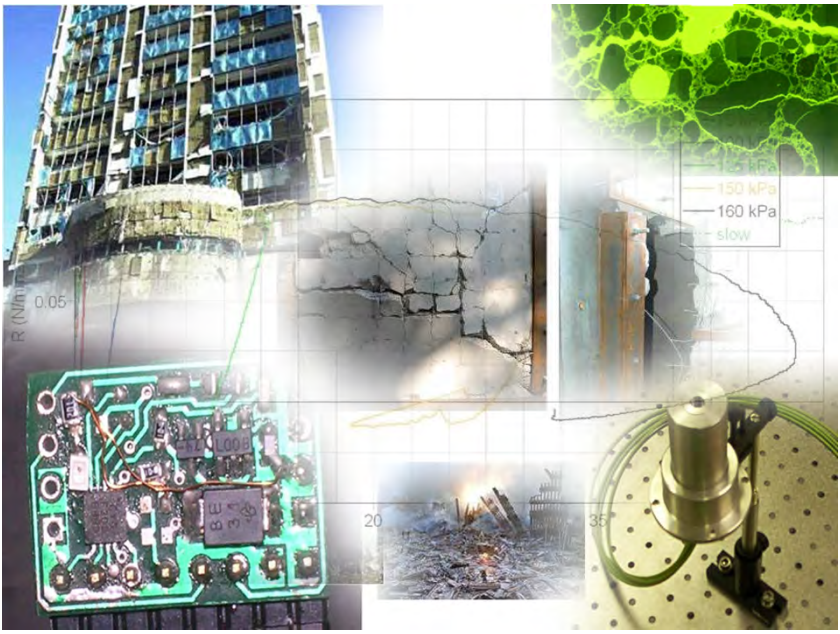
THEME 5

WARNING SYSTEMS



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RISK, RELIABILITY, UNCERTAINTIES: ROLE AND STRATEGIES FOR THE STRUCTURAL HEALTH MONITORING

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Abstract: In urban areas, severe hazardous scenarios can occur with nonnegligible frequency. Large cities are complex systems, in which several complex subsystems interact. Some of the interacting subsystems are only slightly influenced by the others, but can impact heavily themselves onto the others. The structures of civil and industrial constructions have such nature. The vulnerability reduction and control is a task that shall be programmed in condition of limited resources. Structural Condition Monitoring (CM) can help to manage it efficiently. Most of the strategic constructions to which a monitoring system can be applied are existing buildings, sometimes ancient, whose mechanical behavior is hard to assess due to large uncertainties. A reliable monitoring application shall be robust and resilient itself. Redundant distributed sensor networks, designed after an accurate risk analysis, shall have reasonably low cost. Data management, damage assessment and model updating procedures shall be stochastic and robust themselves. Holistic dynamics and multimodel optimization are effective methods with common characters.

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1. Introduction

Resilience and robustness are words having similar meaning in different contexts. Both underline the ability of systems to survive local or extended failures or catastrophic events without significant modifications and identity losses.

Urban systems are collections of complex subsystems, social relationships and security, health care organization, transportation and communication networks, infrastructures and lifelines, buildings and structures.

The complexity of the whole urban system is not merely the sum of the complexities of the individual subsystems, it is largely increased by the interactions between subsystems. It is reasonable to assume that a general urban system is more resilient if the interaction between subsystems is such to damp and soften the response of each individual subsystem to critical events.

Civil structures can be regarded as elements of a first level subsystem. Their response and behavior are little influenced by other subsystems, but the effectiveness of their performance under multiple risks can cause strong impact on them.

So, let us focus:

- On the structural vulnerability assessment and reduction as a key and first-step choice for an efficient control of the urban resilience
- On maintenance plans as the key action to effectively reduce the structural vulnerability
- On the on-line monitoring as the key tool to design a reliable and cost-effective monitoring plan, in which measures and observations help to decide when and where to refurbish and retrofit

Moreover, the modern technology allows environmental security and structural safety oriented sensors to share the same data acquisition and processing network, towards the realization of “smart cities.”

Of course, transforming civil constructions into smart objects is a problem of priority choices in condition of limited resources. Whichever can be the criteria leading to these priority choices, a number of “strategic” structures, so defined because of their social importance or

the heavy danger that their vulnerability induces, directly or indirectly, could be selected to wear a monitoring system. Most of these "strategic" structures are existing constructions; often, they are relevant members of the historical architectural heritage. This means that the knowledge and prediction of their mechanical behavior is affected by large, often very large, uncertainties.

2. On-Line Monitoring on Existing Structures

The past life of an existing structure is seldom fully documented. Therefore, a detailed investigation to detect the present behavior and state shall precede the design and installation of an on-line monitoring system. In both phases, the uncertain knowledge requires robust approaches, as it will be shown with more detail ahead.

A fundamental problem remains open: damage-detection-oriented monitoring is an eligible choice if it can replace with higher efficiency and lower cost the traditional inspection methods. It requires the reasonable certainty that the automatic measurement and diagnosis systems making "smart" a structure can effectively detect all the major damages threatening the safety of the structure. It is not a trivial problem. It is necessary to face the problem of diagnostic monitoring in a more systematic and strategic way. In other words, it is needed a sort of "Copernican Revolution" focused on the damage scenarios, hinging around them the choice of the investigation methods and the automatic observation systems. Identifying damage scenarios and their probability of occurrence requires existing bases of knowledge to be explored whenever available, and/or simulations, relating each possible damage scenario to the severity of its consequences and the meaningfulness of its symptoms. Permanent monitoring systems are, as a matter of fact, symptom measuring systems. It is therefore necessary to evaluate how sensible each symptom is with respect to the damage which produces it and to its severity, and which type of sensor is more adequate to reveal that symptom and how large its sensitivity and its resolution power must be. The importance of this type of approach resides in attributing reliability to the structural monitoring, avoiding the risk of searching for irrelevant symptoms while neglecting more relevant ones.

Moreover, the monitoring system shall be "robust." In technical language, the word "robust" applies to every algorithm, process, method,

or technique able to reduce the sensitivity of analysis results against input data errors or uncertainties. “Robustness” is often associate with the “complexity” domain related to uncertain, redundant data treatment, multivariate event interactions and nonlinear problems, that is the usual condition of the existing structures.

Robust monitoring does not obey to stiff and always valid rules, but one can trace some general criteria to better understand and define its domain:

- Stochastic approaches give more reliable answers than the deterministic ones, because mechanical, physical, or thermodynamic properties can be achieved only through measures affected by errors; the concept of correlation shall replace the concept of causality; stochastic optimization procedures are often required to make that numerical models fit well the experimental evidence.
- Redundancy of data is helpful, although the treatment of redundant data requires some more efforts both in sensing network design and in data-mining techniques application; redundancy helps to reduce local errors but can lead to the wrong assumption that correlated data supply independent consistent information.
- Parallel computing processes can be more robust than sequential computing processes; neural and genetic approaches can prove being very effective.

3. Risk, Reliability, Symptoms, and Damage

Risk and reliability are probabilistic concepts. Often, in literature, the stochastic variable is time, and the probability is the probability of time delay to the occurrence of a predefined damage limit state. The probabilistic distribution becomes a stochastic process in which time-dependent material degradation, fatigue problems, and the prediction of residual life can be easy to model and easy to combine with the risk analysis related with environmental offences, like earthquakes, floods, strong winds, landslides. The reliability of a structure, $R(t)$, is defined then as the probability that the time to reach a reference limit state, t_b, is greater than a given time t (Lawless, 1982):

$$R(t) = P(t \le t_b) \,. \tag{1}$$

The hazard function, $h(t)$, specifies the instantaneous rate of reliability deterioration during the infinitesimal time interval, Δt, assuming that that integrity is guaranteed up to time t:

$$h(t) = \lim_{\Delta t \to 0} \frac{P\left(t_b < t + \Delta t \;\middle|\; t_b \geq t\right)}{\Delta t}. \tag{2}$$

Function $h(t)$ is correlated to the reliability function, $R(t)$, by the following relationship:

$$R(t) = \exp\left(-\int_0^t h(x)dx \right). \tag{3}$$

Nevertheless, following such path, it results in including not trivially in the risk analysis the advantages offered by the application of on-line CM.

To mark the role of the on-line monitoring, it is convenient to jump from the time domain into the symptom space. The symptom hazard function, $h(S)$, is the reliability loss rate vs. the symptom increase rate; then, reliability can be rewritten as a function of the symptom variable, S, as it is the probability that a system, which is still able to meet the requirements for which it has been designed, displays a value of S smaller than the value S_b corresponding to the reference limit state (Cempel *et al*., 2000):

$$R(S) = P(S \leq S_b \;|\; S = \text{suitable value}) = \int_0^S f_S dS \tag{4}$$

and

$$R(S) = \exp\left(-\int_0^S h(x)dx \right). \tag{5}$$

This formulation includes continuous time (slow degradation) or/and discrete time processes (earthquakes, storms, etc.), given that time and symptom evolution can be correlated by suitable laws.

So, as focused above, CM is essentially a search for structural or material disease symptoms. Symptoms can be regarded as evolutionary and sudden changes in observable qualitative properties and/or measureable responses. Symptoms search can require a knowledge-based

direct search or model-based predictive assessment. In both cases, a stochastic procedure is needed. In some applications, direct search and model-based simulations can provide an integrated procedure.

In the works by Cempel (see, e.g., Cempel, 2003), the symptom-based on-line Structural Health Monitoring (SHM) is applied to mechanical systems. Mechanical systems can be often grouped into types and classes with common properties. Large experimental data-bases are in many cases available and accessible; this makes it possible to use symptoms to detect damage on knowledge base. That approach, known also as "Holistic Dynamics," does not need a reference FE model.

3.1. A ROBUST CONDITION MONITORING APPROACH

The approach proposed by Cempel, well fitting the definition of "robustness" given above, is here discussed in some detail.

Mechanical structures in operation and machines vibrate. Vibration is a good carrier of structural and condition-related information. Measuring vibration signals and processing them (by some fast time-averaging operation, for instance) provide symptoms of condition. Symptoms are evolving (usually growing) during the system life, giving good mapping of operational condition of a system. Having some additional historical records of observed symptom values, it is possible to create condition inference rules concerning reliability and risk issues of the system, and eventually to develop 'go/repair' decision rules which ultimately lower the risk of operation. Such is the idea behind CM of a system: from signals to symptoms and to system condition.

In traditional approaches, this is usually done on the basis of one symptom–one condition measure. The measuring technology of today, however, enables to measure many life-dependent operational and residual processes as symptoms, therefore allowing the creation of symptom observation matrices.

Cempel exploits such multidimensionality of the symptom space in order to elaborate some independent measures and indices for further inference with a high confidence level. An approach is there presented for multidimensional CM of mechanical systems in operation, in particular, machines. This multidimensional approach is made possible by the use of the transformed symptom observation matrix (SOM) and

by successive application of singular value decomposition (SVD). On this basis, one can obtain full extraction of fault-related information from symptom observation matrix by traditional monitoring technology, and also create several independent fault measures and indices. In other words, SVD allows to pass from the multidimensional-nonorthogonal symptom space to the orthogonal generalized fault space, of much reduced dimension. This seems to be important, as it can increase reliability of CM of critical systems in operation and can maximize the amount of condition-related information in the primary symptom observation matrix, pushing towards a redesign of traditional CM systems.

3.2. THE SYMPTOM OBSERVATION MATRIX AS THE INFORMATION RESOURCE

Symptoms may be any measurable quantity which is sensitive to system modifications. Additionally, symptoms should be sensitive to damage evolution but insensitive to distortions. Direct reference (Cempel, 2003) is made to vibration measurements as helpful symptoms, particularly, as the average (or root-mean-square) values of the time-history records over some time-span, but various kinds of either global or local symptoms can be generally chosen, including constants, functionals, vectors, functions, field descriptions, either taken as the response to operating/service forces or as the response to purposely applied test forces.

Supposing now that r symptoms S_m, $m = 1, 2, \ldots, r$, are measured at p instants θ_n, $n = 1, 2, \ldots, p$, over the system life, the observation matrix may be defined as:

$$O_{pr} = \left[S_{nm}\right] = \left[S_m\left(\theta_n\right)\right], \; n = 1, 2, \ldots, p, \; m = 1, 2, \ldots, r \tag{6}$$

with m as the number of columns (symptoms) and n as the number of rows (lifetime readings). When symptoms are well chosen and the system operation is stable, the observation matrix is a valuable resource concerning the system condition and evolution of the system properties.

Since, in general, the observed symptoms have different physical origin and therefore different physical units, range, and initial values, it can be shown (Natke and Cempel, 2001) that the subsequent feature

extraction is improved if O_{pr} is preliminarily normalized, i.e., every symptom is first column-like divided by its initial value and then centred on it.

Furthermore, since many critical structural systems operate in a non-stationary load regime, and many observed symptoms depend in some way on load and/or environmental conditions, the CM of such systems should have some possibility of rescaling of the observed symptoms to a standard load condition (Cempel and Tabszewski, 2007).

In any case, the resulting observation matrix can be a huge matrix. Some symptoms can be correlated with others and unusefully redundant. This is why, the normalization above being accomplished, SVD can be profitably applied to SOM in order to extract different generalized fault modes evolving in the system:

$$O_{pr} = U_{pp}\Sigma_{pr}V_{rr}^{T} = \sum_{t=1}^{z}\sigma_t\left(u_t v_t^{T}\right) = \sum_{t=1}^{z}\left(O_{pr}\right)_t \text{ , } z = \min(p, r), \qquad (7)$$

where $t = 1, 2, \ldots, z$, σ_t are the singular values, u_t and v_t are the (orthogonal) singular vectors, as columns of the respective matrices U_{pp} and V_{rr}.

As a result of SVD, the symptom observation matrix O_{pr} is represented as the summation of z independent matrices $(O_{pr})_t$, each describing a specific mode t of system operation modification (evolution), or generalized fault mode. Tracing the evolution, through the lifetime θ, of the fault modal parameters, $\sigma_t(\theta)$, $u_t(\theta)$, $v_t(\theta)$, and $(O_{pr})_t(\theta)$, gives an understanding of the system conditions. Especially useful is the time evolution of the so-called generalized fault symptom $SD_t(\theta) = O_{pr}(\theta)v_t(\theta) = \sigma_t(\theta)u_t(\theta)$, which represents a weighted summation of the symptom values for each lifetime θ and can be shown to give information on both the shape of a generalized fault and its energy.

It can also be easily shown that singular values and singular vectors in the SVD can be equivalently obtained through solving the eigenvalue problem for the matrices $W_1 = O_{rp}{}^{T}O_{pr}$ and $W_2 = O_{pr}O_{rp}{}^{T}$. In particular, the matrix W_2 is similar to the correlation/covariance matrix in stochastics: through its values, it characterizes the orthogonality between the lifetime-dependent symptom vectors. Also, it gives information on the quality of the choice of the vectors with respect to the lifetime

modifications: large values of the out-of-the-main-diagonal elements indicate linear dependency of the symptoms, which means redundant information with respect to θ.

Using both generalized fault indices $\sigma_t(\theta)$ and $SD_t(\theta)$, the first related to the intensity of wear advancement in a given fault mode and the second to its momentary shape, instead of the original symptom observations $O_{pr}(\theta)$, allows a more concise and powerful representation of system conditions. In this sense, SVD plays the same role of eigenvalue decomposition in system dynamics and of principal components analysis (PCA) in statistics. However, SVD seems preferable in CM applications than PCA since the latter is less sensitive to small energy components of the observation matrix due to matrix multiplications inherent in PCA.

3.3. SVD MEASURES OF SYSTEM CONDITIONS

But what can be the equivalence between the wear characteristics and measures of the operating system and the SVD parameters?

From the physical viewpoint, different wear modes can occur like corrosion, fatigue, erosion, etc., but the influence of different types of wear modes working concurrently in a system in operation can be very similar, when observed in a symptom space, so we cannot differentiate them in this way. In other words, physically different types of wear can generate similar signals or symptoms, and there is no way of finding the expected difference in the resource of the symptom observation matrix. This means that the transformation from the space of physical wear to the symptom space is not unique and unequivocal. Hence, looking for fault description in the symptom observation matrix, only some generalized faults $F_t(\theta)$ can be mathematically identified without getting to know their direct physical and/or operational origin. From that point of view, it is of paramount importance to proper choosing (physical origin, place of measurement, signal processing, etc.) each observed symptom $S_m(\theta)$ during the system operation.

And since in the system in operation several generalized faults may be evolving concurrently, like rotor unbalance, bearings faults, misalignment, etc., then it is important to know also the global advancement of all generalized faults in a system.

Hence, some global indices are needed. It can be shown that the best choice appears to adopt the sum of absolute values of singular values:

$$DS(\theta) = \sum_{t=1}^{z} \left| \sigma_t(\theta) \right| \tag{8}$$

as the measure of wear advancement, and the sum of absolute values of singular vectors:

$$P(\theta) = \sum_{t=1}^{z} \left| SD_t(\theta) \right| \tag{9}$$

as the measure of the generalized fault profile.

Summing up, it seems possible to pass from multidimensional symptom space with high redundancy to generalized orthogonal fault space with very few generalized faults $F_t(\theta)$. It is also useful to create some combined measure and indices on a system condition, in terms of some norms of the symptom observation matrix, its singular values, and SVD-related summary measures and indices.

4. Condition Assessment on Existing Civil Structures

Existing civil structures are generally nonstandard, unique and non-constrained into types and classes. At the beginning of the monitoring action, useful data and knowledge bases are seldom available. Such situation configures the phase of initial assessment of the present state. From now on, the analysis of damage evolution will move its steps.

Unfortunately, the initial condition is not necessarily an undamaged condition, so its assessment shall include damage scenarios and their detection and identification.

The lack of real damage knowledge bases makes numerical simulation on FE models the only practical way. If only model based simulation is available, then the damage assessment using the SOM converges to the so-called “multimodel approach” to model updating.

First, let us assume that the SOM allows to relate damage indices to symptoms, originally intended as changes in modal and statistical parameters extracted from vibration signals, but extendable to more general symptom spaces.

Due to uncertainties and errors, we can assume that each damage state can generate infinite symptom sets, in which each symptom can change in agreement with a given probability distribution.

If we use models and simulation, probabilistic procedures (including Monte Carlo search) allow to generate many structural models by changing randomly material and mechanical properties; consequently, many sets of damage scenarios and symptom sets can arise.

The final goal is to extract damage states and their probability from the analysis of observed symptoms.

The size of the observation matrix, its multidimensional and multivariate stochastic nature, nonlinearities, intrinsically included in the real damage-symptom causality and the randomness of measures and environmental conditions in which symptoms are extracted, make it hard to solve the inverse problem.

It is necessary to reduce the size of the problem and, at the same time, to prevent correlate symptoms treated as independent variables from generating noise and leading to incorrect solutions.

As for the "holistic dynamics" approach, the master path goes through the Principal Component Decomposition or Proper Orthogonal Decomposition, that are in fact different definitions of the same technique, being both based on SVD.

By applying the SVD to the observation matrix, conveniently normalized and transformed, the operational space is reduced and inversion made easier. In other words, full utilization of SVD enables to pass from multidimensional-nonorthogonal symptom space to orthogonal generalized fault space, of much reduced dimension. This seems to be important, as it can increase the reliability of CM of existing structural systems in service. It enables also to maximize the amount of condition-related information in the primary symptom observation matrix, and redesign the traditional CM system.

This kind of approach contains an implicit idea of causality. If we want to reason in terms of "conditioned probability," instead of cause-effect, we can look at the CM using symptoms observation as a typical Bayesian problem. All model-based characterization methods belonging to the class of "multimodel" approaches can be associated to the Bayesian stochastic theory. An example of a multimodel approach to characterize an ancient masonry structure will be shown later.

It is important to stress out that this kind of philosophy is based on the choice of the best fitting solution among many candidates generated

randomly in a direct way. In such a way, the trap of the ill-conditioned nature of inverse approaches is avoided. The method is robust given that the initial choice of damage scenarios is correct and sufficiently exhaustive.

4.1. THE MULTIPLE MODEL APPROACH TO OPTIMAL MODEL CHOICE

The presence of damages and uncertainties inside an existing structural body makes that the mechanical properties of the structure are affected by a local variability that cannot be assessed *a priori* in deterministic way.

For these reasons, we wish to generate multiple models for achieving the right solution; but what do we mean by "multiple model"?

We can talk about multiple model approach in two different cases:

1. Candidate models belong to different classes having different sets of parameters (heterogeneous model set).
2. All candidate models have the same structure with the same set of variables and differ only in the value of continuous variables (homogeneous model set).

In both cases, different models can be representative of different "damage scenarios" so as they came out from a preliminary risk assessment.

However, the two situations are different in the face of data mining techniques. The first case is difficult to automate. Current data mining techniques are unable to accommodate data containing different sets of parameters. A semiautomatic procedure can be applied in the case of heterogeneous models where the user manually separate models into classes using their knowledge of important parameters. On the contrary, data mining techniques may be very useful to discover different types of data patterns in the second case.

No matter which case is under consideration, the multiple-model approach consists of two distinct phases: the multimodel generation (direct phase) and the final selection of the best-fitting model/models (inverse phase). Some hints are given below to the multiple-model approach as adopted by Smith *et al.* (see, for instance, Smith *et al.*, 2006).

4.1.1. *The Direct Phase*

In Smith's approach, once the objective (target) function has been introduced as a quadratic cost function based on the average error between measurements and model predictions, a stochastic optimization algorithm, known as Probabilistic Global Search Lausanne (PGSL), is used for model generation and minimization of the said cost function. In fact, PGSL is an iterative process including 4 nested loops, originally developed to solve generic global search optimization problems (Raphael and Smith, 2002) and subsequently specialized to fulfil robust stochastic model updating (Saitta *et al.*, 2005).

Without getting into the details of each encased cycle, it is possible to summarize the main steps of the procedure as follows.

First, a population of m initial models, each identified by a set of n model parameters and thus interpreted like a point in the n-dimensional input variable space, is randomly generated. This is accomplished by initially assigning each model parameter a uniform probability distribution in a predefined range (i.e., by dividing this range into p equal intervals with the same probability) and then by randomly extracting m values from that distribution. Correctly choosing the parameters' range is obviously as necessary as properly selecting the updating parameters and describing the mathematical model (i.e., finding the relevant damage scenarios), in order to obtain trustworthy results.

The initial generation is therefore evaluated through the assigned cost function, the best model is identified, and the probability density for each parameter is increased in the interval about the value taken by the best model and progressively decreased with the distance elsewhere.

Through parting the intervals having higher probability density into smaller subintervals, the probability density distribution is refined and used for the next iteration to generate a further set of m new models. In this way, the determination of models that constitute the database takes place in a not-deterministic way, solving the risk of entrapment, even if guided by the evaluation of antecedent ones.

The process continues until predefined convergence criteria are met. The basic idea of this approach is that a better solution may be found near a good one. At convergence, a distribution is obtained, centered around the best result, whose shape itself may give information on the uncertainty of the updating. Additionally, as better explained

next, all the models encountered (and stored) during the iterative process can be of great help in discussing the robustness of the solution, thanks to the features extraction techniques applied in the inverse phase.

4.1.2. *The Inverse Phase*

The second part of the updating process consists in the evaluation of generated models.

A preliminary filtering is operated by excluding all the models for which a conveniently chosen penalty function exceeds a given threshold.

Once the set of selected models is defined, the analysis of the models must be performed. All selected models have the capability to describe the behavior of the real system, so we are confronted with the problem of extracting information from data. Discerning the significant patterns in data, as a first step to process understanding, can be greatly facilitated by reducing dimensionality. The *superficial dimensionality* of data, or the number of individual observations constituting one measurement vector, is often much greater than the *intrinsic dimensionality*, the number of independent variables underlying the significant nonrandom variations in the observations. The problem of dimensionality reduction is closely related to *feature extraction.* Feature extraction refers to identifying the salient aspects or properties of data to facilitate its use in a subsequent task, such as classification. Its features are a set of derived variables, functions of the original problem variables, which efficiently capture the information contained in the original data. The similitude with the size reduction problems in the SOM is clearly evident.

For this purpose, some data mining technique can be applied such as Principal Component Analysis (PCA) and clustering techniques.

Principal component analysis is used abundantly in all forms of analysis—from neuroscience to computer graphics—because it is a simple, nonparametric method of extracting relevant information from confusing data sets. With minimal additional effort, PCA provides a roadmap for how to reduce a complex data set to a lower dimension to reveal the sometimes hidden, simplified structure that often underlie it. Principal component analysis seeks the linear combinations of the

original variables such that the derived variables capture maximal variance. It can be done via the SVD of the data matrix. Data representation in the principal component system corresponds to a change in referring system.

Clustering techniques are helpful in classifying a given set of models into homogeneous groups, represented in the space of the model parameters by points close to each other. A technique for collecting similar model into few groups represented each-one by "flag" model, corresponding to an averaged set of parameters, is the "*k*-means" method. The base tool of this technique is the Euclidean distance: each model is "captured" by the group having the minimum Euclidean distance to it. Its parameters concur to the averaging process that defines the slightly evolving coordinates of the centroid of the group (i.e., the flag model). The solution obtained in this way is strongly conditioned by *k* value, which is defined by the user; especially in cases in which it is impossible to visualize graphically the distribution of models in space, it is very difficult to choose the number of clusters and it is hard to anticipate the result of choice: for this reason, the base algorithm is inserted inside an external iterative structure, finalized to search the optimum *k* value. The basic criterion for the optimal search is related to the ratio between the average Euclidean distance inside each group and the distance between the centroids of different groups.

4.2. SENSORS FOR "ROBUST" MONITORING

A preliminary risk analysis and damage scenarios assessment should always drive the measure system design. The goal is to build-up a priority list of the expected damages and structural problems. Such kind of approach philosophy, although potentially useful for every SHM application, is not always easy to apply in practice, due to lack of systematic knowledge-bases related to observed damages in similar structural objects in the past.

The preliminary risk analysis is useful to select in a rational way the kind of information needed and to design, consequently, the most effective sensors networks. If a reliable knowledge base is not available, then numerical analyses on realistic FE models can offer some help.

Anyway, when the uncertainty level is particularly high, like in case of ancient masonry structures, an effective SHM action requires distributed sensing capability and redundant in space and time data

collections. Distributed sensing means many sensors and a huge amount of data to handle.

Of course, “many sensors” implies “low-cost sensors.” Sensors can be made at low cost through either inventing new technologies that will become “low-cost” if they will spread-out; or conceiving low-cost technologies from the beginning (hard to do without any loss in reliability and resolution); or “stealing” existing technologies from existing mass-produced applications and adapting them.

“Huge amount of data” implies the necessity of techniques to select, pack, compact them and of an architecture of the sensor networks allowing a hierarchical behavior and a local preelaboration in the peripheral nodes.

Recent technological progresses in micro-electro-mechanical systems (MEMS), wireless communications, and digital electronics have allowed the development of Sensor Nodes, i.e., small multifunctional low-power and low-cost devices, which are able to communicate between them through limited beam wireless technology. These small Sensor Nodes are made of components able to find perceptions, elaborate data, and communicate with each other. Indeed, nodes are provided with an on-board processor; therefore, every node, instead of sending “crude” data to the nodes responsible of the data gathering, can just carry out simple elaborations and transmit required and already processed data. A very important problem to consider while realizing a sensor network of this type is the one of the energetic consumption. Just for this reason, such networks are realized with cross-layer architecture in which the sensors are distributed on routing tree that concurs to optimize the transmission of the data between the sensors and with the node sink, allowing the maximum energetic saving.

Recently, data mining techniques have been introduced in such sensor networks in order to obtain better results in the monitoring. For instance (Green, 1987; Mishing, 2004):

- Clustering, used for the partition in a jam of date
- Fuzzy Adaptive resonance theory (ART), to provide an architecture to the sensors in the network, when they operate within unsupervised learning with a consequent characterization of the input from sensors
- Algorithm EM, to optimize data analysis procedure when data are supplied from a not perfectly working sensor network

4.3. STRUCTURAL IDENTIFICATION AND CHARACTERIZATION

Vibration based on-line testing shall be operated in service conditions. Output-only acceleration or velocity records are generally produced by low-energy excitations. It is reasonable to assume that the structural response remains almost linear inside the measure amplitude range. Nevertheless, the quasi-linear character of the response is the effect of a local linearization depending on the static preload and environmental conditions. Service input is generally nonstationary. In nonstationary conditions, classical Fourier analysis should be replaced by the more general time-frequency analysis. Currently, the algorithms used for time-frequency identification belong to three main branches: short-time Fourier transforms, wavelets and wavelet filter banks, Cohen-class bi-linear transforms.

Although wavelet transforms captured the attention of the largest part of researchers worldwide, the authors focused their attention to the bi-linear transforms, due to their powerful intuitive properties and their high resolution both in time and frequency, independently on the frequency range (Figure 1).

A method has been recently proposed that works out instantaneous quantities (Time-Frequency Instantaneous Estimators or TFIE, see Bonato *et al*., 2000), such as the phase difference and the amplitude ratio between channels, as a function of frequency. In linear systems, modal components are recognized since they show estimator values that are characterized by stability over time. The estimators are defined on the basis of the time-frequency analysis of vibration response signals, so these techniques might be placed into a new class of time-frequency domain methods.

5. Case Study: the Holy Shroud Chapel in Torino

Designed by Guarino Guarini, built from 1667 to 1694, this outstanding baroque construction was heavily damaged by fire in 1997, right after a general restoration (Figure 2).

After the fire, the Supervisor for Architectonic Assets committed to the Politecnico di Torino the project for a general experimental campaign on materials and structure (P. Napoli) and a dynamic test programme (A. De Stefano), and charged the Politecnico di Torino

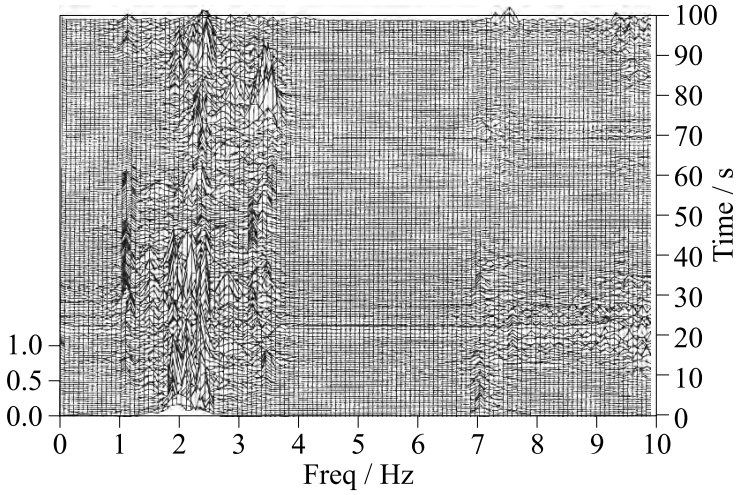

Figure 1. Bi-linear Cohen-class autospectrum of an accelerogram recorded from a real structural vibration test; different modulated-harmonic components reach the maximum energy level in different time intervals.

(A. De Stefano) and the University of Kassel (M. Link) of the numerical model refinement and the experimental model updating.

This latter activity ended on 2003, well before the programmed test campaign. At that stage the model updating could be based only on a very limited set of vibration signals recorded during an unofficial test.

In May 2006, several vibration tests were executed on the dome, using four different dynamic inputs:

- Environmental excitation (traffic, wind, microquakes)
- Impulsive excitation produced by hammering
- Impulsive excitation caused by a sphere dropped to the ground near the base of the building and
- Wind turbulence produced by a helicopter of the Fire-Police flying around the dome top

A total of 25 accelerometers were used on six different levels, measuring the response in radial, vertical, and tangential directions, and the resulting signals were used to perform the structural identification of the dome. The signal processing procedures were applied to the

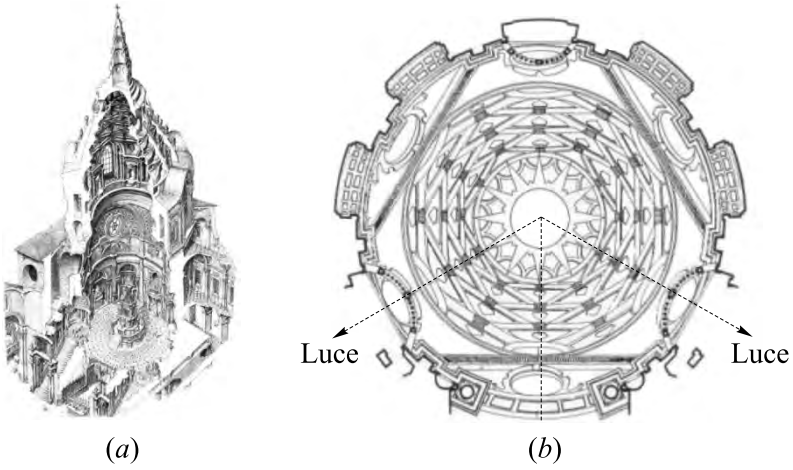

Figure 2. Axonometric section and planar section of the dome.

records as they were acquired, in the cylindrical reference system, and also to their transformed components in a Cartesian orthogonal reference system.

5.1. MODAL IDENTIFICATION

Dynamic identification was performed through the TFIE method. Modal frequencies were identified using different combinations sampling frequency (25 to 50 Hz) and signal length (256 to 512 samples).

The TFIE diagrams computed from signals with identical sampling frequencies and lengths were averaged. By properly selecting the coordinate reference system and the record set, the downward peaks marking modal frequencies are clearly visible (Figure 3). Applying the TFIE analysis to the x oriented signal components in a Cartesian reference system, one can easily reconstruct the modal shape projection on the x–z plane, where z is the vertical axis. In general, it results convenient to use signals in cylindrical coordinates to identify modes where the torsion is prevailing whilst Cartesian coordinates work better to extract modal shapes with prevailing translation. The records obtained under the excitation of the dropped sphere supplied the best results. In this way, it was possible to resolve two modes very close to each other at $f_1 = 2.246$ Hz and $f_2 = 2.344$ Hz.

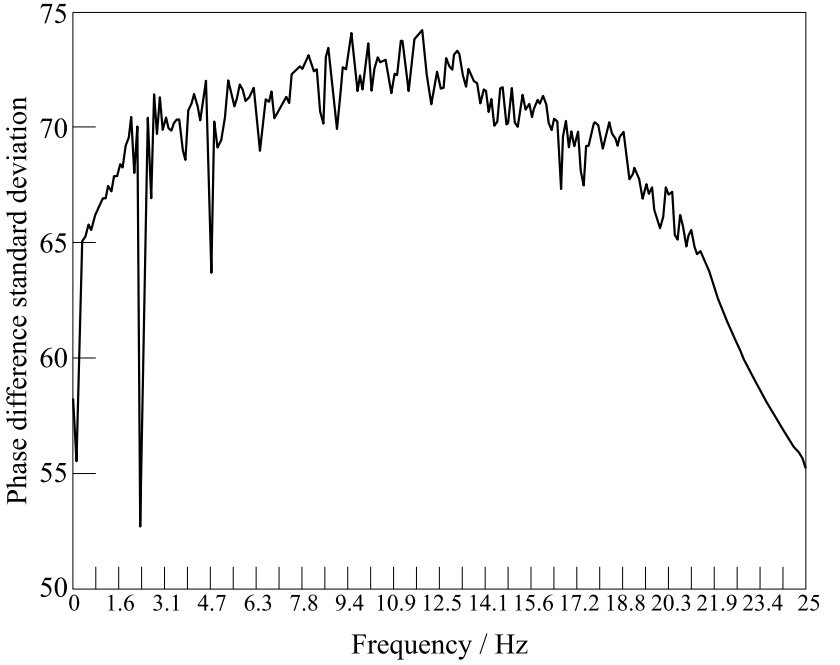

Figure 3. Phase difference standard deviation (PDSD) dir.X—f_2 = 2.344 Hz.

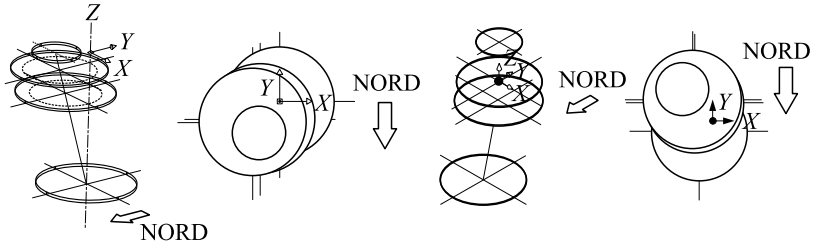

Figure 4. Identified mode shapes: (*a*) first mode (bending); and (*b*) second mode (bending).

Modal shapes were identified using the same data pairs and sampling conditions which provided the best results in the frequency search. The first flexional shape is directed in NE-SW direction, the second—in NW-SE direction (Figure 4).

5.2. THE MULTIMODEL APPROACH TO OPTIMAL MODEL CHOICE

In the case study, a roughly simplified preliminary application of the multimodel strategy was used. Symptoms were reduced to the first 5 modal frequencies and a cost function, based on the differences between the identified and computed values, was calculated; the process was completed with an estimation of the error in the prediction of the corresponding modal shapes. The parameters to be updated were chosen to correspond to the material's elastic modulus in different substructures or homogeneous zones of the FE model. The stiffness of some spring-type connections accounting for the interaction with neighbouring buildings was let vary as well.

Based on a sensitivity analysis, only substructures outlined in Figure 5 were selected for updating, the remaining parameters being kept constant.

The multimodel approach was therefore implemented. Through a focused, or biased, random search of the domain of selected parameters based on the PGSL algorithm, convergence was attained to the global minimum of the assigned penalty function. As a by-product of PGCL and yet as a fundamental ingredient of multimodel updating, during such iterative convergence, several tentative models were encountered. Those among them which were found to be "good" (i.e., whose penalty function was found less than a given threshold value) were taken, in a robust perspective, as plausible candidate representations of the real structure. Properly weighing the speed of the convergence and the exhaustiveness of the research, it was possible on the one hand to find the actual numerical global optimum, on the other to meet a variety of good (suboptimal) candidates.

Once defined, the population of reasonable candidate models, data mining strategies were available in order to classify them into homogeneous sets and to discuss the robustness of the updating procedure, as well as to reduce information. To this purpose, PCA enabled reducing the original domain of five independent physical parameters to the new domain of three principal components, capable alone of represen-ting alone 90% of the variation of the entire population of good candidates models. On the other hand, using a clustering method of the *k*-means type, it was eventually possible to categorize the whole of good models into a certain number of homogeneous classes, each

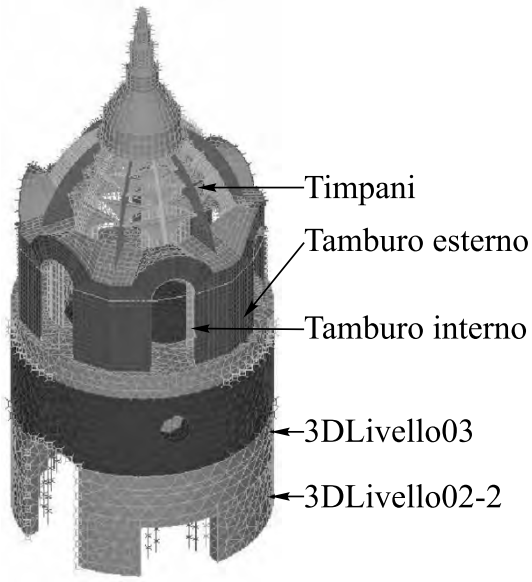

Figure 5. Updated substructures in the finite element model.

centered around a centroidal model. Observing the limited variability of physical parameters among different centroids (Table 1), it was possible to appreciate that a small uncertainty affects the updating procedure, which seems to have attained a certain degree of robustness.

TABLE 1. Physical model parameters (E_6, E_11, E_12, E_18, E_19) defining the centroidal models (M_1, M_2, M_3, M_4, M_5) after a clustering procedure

	E_6	E_11	E_12	E_18	E_19
M_1	2.9198 E+08	1.2858 E+09	2.8375 E+09	2.1315 E+09	1.9101 E+09
M_2	2.4771 E+09	1.2784 E+09	2.8678 E+09	2.0406 E+09	1.9227 E+09
M_3	2.4321 E+09	1.2994 E+09	2.6620 E+09	2.0999 E+09	1.9104 E+09
M_4	2.1573 E+09	1.2910 E+09	2.8273 E+09	2.4956 E+09	1.9362 E+09
M_5	2.5294 E+09	1.3252 E+09	2.874 E+09	2.4956 E+09	1.9514 E+09

6. Concluding Remarks

Condition Monitoring is a tool to keep under control the health conditions of relevant structures and to help decision making related to maintenance priorities. Condition Monitoring requires distributed

sensing systems (hardware) and reliable data treatment procedures (software). The present contribution does not enter deeply into the sensing technology. It has been stressed out that distributed sensing means low-cost technologies. Until now, the most of monitoring systems are based on point-wise sensing devices connected in networks. The modern trend, however, is towards physically distributed systems, where the construction and coating materials themselves have sensing capabilities. Vectorial properties of stress and strain fields will be replaced by scalar functions, which will require accurate interpretative models. Damage assessment procedures need to be robust to reduce the influence of local errors and uncertainties. The two methods illustrated above are focused on different goals, but they have several common aspects: both belong, in wide sense, to the domain of stoch-astic Bayesian methods; both rely on the quality of the damage scenarios that make the initial knowledge a base for simulations project. Both avoid inversion of large problems using data mining tools to reduce their size. Both allow a consistent physical and intuitive control on the outcoming results.

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DISTRIBUTED OPTICAL FIBER SYSTEMS FOR STRUCTURAL HEALTH MONITORING

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Abstract: The physical and mathematical principles of distributed optoelectronic measuring systems (MS) and networks for structural health monitoring are developed. There is developed a complete set of a theoretical and experimental data allowing designing a point and distributed phase optical fiber sensors (OFS) on the base of single-fiber multimode interferometers (SFMI) and Fabri–Perot fiber interferometers (FPFI). The principles of integrated measurements by the distributed and extended OFS and are investigated. There is developed the optimal topologies of tomography measuring networks and worked out the recommendations for type of sensitivity of used extended OFS which provide optimum conditions for the measuring data acquisition and for the reconstruction of distribution of controllable objects parameters. There are developed algebraic and neural network algorithms allowing to solve the reconstruction problem for various types of physical fields (PF) inside objects under monitoring, in conditions of measuring data incompleteness and in real time. The basic problems appearing at the distributed optoelectronic measuring networks and system's parameters perfection and their large-scale practical application are determined.

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Keywords: distributed optical fiber measuring systems; structural health monitoring; optical fiber sensor; fiber tomography measuring networks

1. Introduction

The modern civil engineering encounters various challenges concerned with highly intensive usage of buildings and structures, which is often complicated by harsh environmental conditions, chemically active mediums, fires, threats of terrorist attacks, etc. Therefore, special and often contradictory requirements to building designs and materials are constantly emerging. Accordingly, the following tasks are becoming of increasing importance and interest to scientists and engineers working in civil engineering, structural health monitoring, and MS design:

- Monitoring of durability and integrity of various buildings and structures, including frames, shells and foundations, dams and retaining wall, high-rise building, basic structures, etc.
- Monitoring of destruction processes of materials and constructions caused by cracks and plastic deformations
- Development of MS providing correlation data between construction deformation and possible defects, both initial, and appearing during manufacturing and further exploitation and
- Development of security MS for the discovering of illegal penetration into potentially dangerous objects and locating a trespasser on the area under monitoring

Large-scale application of automated monitoring technology, expansion of fundamental and applied research horizons demand development of various sensors both capable of integration in complex MS and providing reliable real time information on the PF, objects, and processes under monitoring. Therefore, the important problem is the development of modern approaches to organization of measurements, creation of high-speed MS, new technologies of sensor manufacturing providing MS with such essentially important capabilities, as adaptability, integrability, and self-verification and self-correction abilities. Modern measurement techniques make wide use of optical, electrical, magnetical, piezoelectrical, and other types of sensors. Significant progress of optical fiber communication lines (OFCL) technology resulted in the emerging of a new metrology field—OFS. It is clear

now that some of their characteristics are much more preferable to that of conventional sensors. Such advantages of OFS as high sensitivity, high-speed operation, and electromagnetic noise immunity, small size and weight, ability to combine sensing and transmission functions in single a unit, as well as ease of integration with modern communication lines and computing devices, open exciting prospects of the development of essentially new branched MS.

In the last two decades of the previous century, initial researches were performed that have shown significant promise of OFS, which were classified as intensity-based, phase (interferometric), polarization, spectral, and nonlinear optical sensors according to the guided light modulation principle. At the same period, researches in Far Eastern Polytechnical Institute (nowadays, Far Eastern National Technical University) and in Institute of Automation and Control Processes of FEB RAS were initiated aimed at the development of adaptive distributed optoelectronic systems. The purpose of the present work is the review of the results of those researches.

2. Optical Fiber Sensors

2.1. OPTICAL FIBER SENSORS WITH LOCAL SENSITIVITY

An OFS (Figure 1a) consists of three main parts: (1) sensitive element (SE), intended both for the sensing of an external physical effect on the optical fiber (OF) and for transforming it into the change of one of the guided light parameters; (2) signal-transmitting OF; and (3) optoelectronic module. The optoelectronic module normally includes a light source, light input/output unit, photodetector, processing system intended for both transformation of light parameter changes into an electrical signal, or forming a visual image.

In many cases, the procedure of monitoring physical processes and PF requires performing measurement in a certain point of space. Such measurements are usually carried out by sensors with local sensitivity (see Figure 1a). Important features of the “local” sensors are: possibility of sensitivity optimization by varying fiber length, possibility of remote measurements without additive noise level increase as well as total electromagnetic noise immunity (Busurin and Nosov, 1990;

Kulchin *et al*., 2000; Kulchin, 2003; Taymanov and Samozhnikova, 2004; Hongan *et al*., 2004; Smith and Betti, 2004).

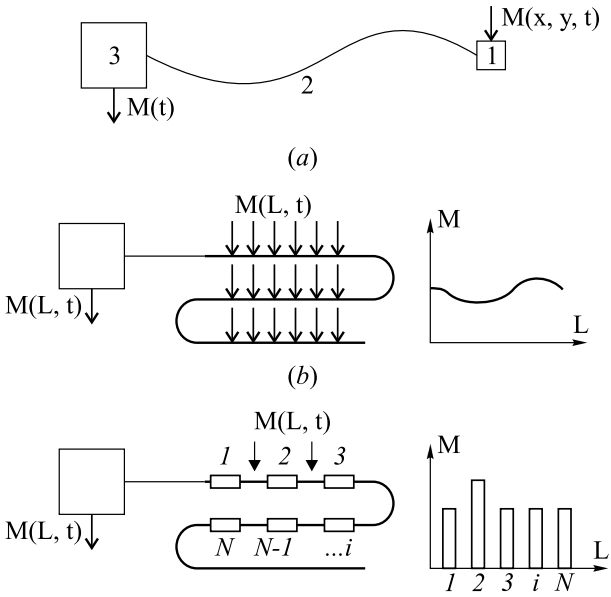

Figure 1. Optical fiber sensors types: (*a*) local (*1*—sensitive element, *2*—signal-transmitting fiber, and *3*—optoelectronic module); (*b*) distributed; and (*c*) quasidistributed (*M*(*L*,*t*)—measuring value).

The last 20 years witnessed the emerging of "local" OFS intended for measuring practically all known physical values with high accuracy (Busurin and Nosov, 1990; Kulchin *et al*., 2000; Kulchin, 2003; Taymanov and Samozhnikova, 2004; Hongan *et al*., 2004; Smith and Betti, 2004).

Our activities were focused on the development of physical principles of the most simple and reliable, intensity-based OFS, and phase sensors as potentially the most sensitive ones.

Figure 2 represents the schematic and photo of the local fiber optic intensity-based inclinometer developed with the operation principle based on the measurement of the light intensity reflected from the interface between liquid and air. There are three fibers to receive the reflected light. The comparison of the output signal from the receiving fibers enables simultaneous measurement of both inclination angle

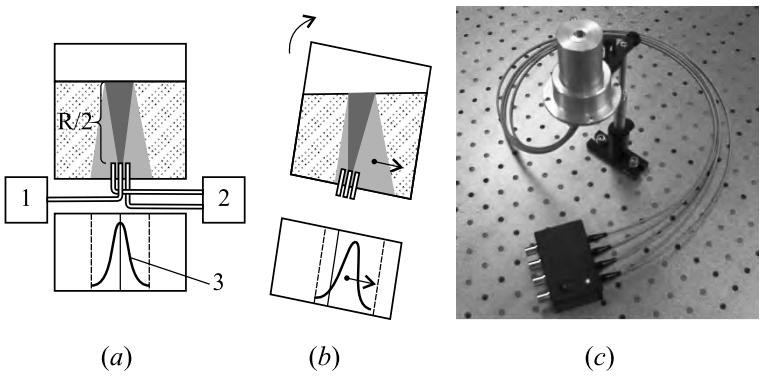

Figure 2. Fiber optic intensity-based inclinometer: (*a*) sensor scheme (*1*—LED, *2*—photodetector, *3*—signal intensity profile); (*b*) reflected light beam shift due inclination; and (*c*) sensor photo.

and direction. Additionally, it provides an opportunity to compensate for measurement inaccuracy resulted from temperature changes, input optical power losses, liquid optical properties variations, and other noise factors. Inclination angle threshold sensitivity of the sensor is 0.01°, azimuth sensitivity is 5°, dynamic range is 50 dB.

As for phase OFS, we basically work with single-fiber interferometers, representing the most simple and noise-protected class of interferometers. The researches were particularly focused on two types of such interferometers: (SFMI) and FPFI.

The optical circuit of SFMI contains a single multimode OF. The interferometer measures changes in phase difference between guided fiber modes caused by external physical effects. The researches performed showed that the intermode phase difference generally depends on the OF elongation and practically does not depend on other factors of deformation, such as fiber bending. It allows one to consider SFMI to be sensitive to the absolute elongation of the OF. During theoretical and experimental researches of coherent and statistical properties of laser light guided by multimode OF, we determined interdependence between contrast, correlation area size, and probability density of the output light intensity distribution taking into account dispersion and geometrical parameters of OF, light source wavelengths, and coherent characteristics. The results obtained allowed us to formulate the requirements to OF and light sources used for local and distributed sensors based on the SFMI scheme.

As a rule, SFMI-based sensors demonstrate high strain sensitivity. However, as a result of multimode interference at the output of SFMI, a complex and contrasting speckle structure appears which greatly complicates the processing of the interference signal. Research results of speckle patterns formed by SFMI has allowed us to develop correlation principles of interference signal processing, using both amplitude and holographic spatial filtration and CCD matrix technology. Theoretical and experimental researches have shown that the correlation signal is a function of the maximum additional phase difference ($\Delta\Phi_{max}$) between modes guided by SFMI: $P_{out}(t) \propto \sin c^2(\Delta\Phi_{max}(t)/2)$. As a result, metrological specifications of SFMI-based OFS are determined by the numerical aperture, length, and material of the OF in use. By varying these parameters, it is possible to achieve threshold sensitivity of SFMI to relative axial deformation from 10^{-10} up to up to 10^{-5}, and dynamic range of 30–40 dB in the static mode.

The developed principles of the amplitude and holographic optoelectronic correlation filtration and CCD matrix technology were used for the development of SFMI signal adaptive processing techniques. It has allowed us to solve the problem of low-frequency fading of the interference signal caused by stochastic influences, such as temperature drift, technological vibrations, incidental mechanical influences, laser wavelength instability, etc. (Busurin and Nosov, 1990; Kulchin *et al*., 2003).

There are two types of optical FPFI: single OF (i) with specular end-faces (intrinsic FPFI), and (ii) with air gap between two parallel specular optical fiber end-faces (extrinsic FPFI).

We investigated both multilayer dielectric covering of TiO_2/SiO_2, as specular coating for FPFI which provide reflectance (R) of 0.3 to 0.9, and a metal wide spectral range specular reflectors with R of 0.05 to 0.95, which were made by depositing thin metal layers (Al, Ag, Au).

In-depth investigations into FPFI characteristics dependence on the parameters of OF and fiber end-face specular coatings have allowed us to formulate the principles for FPFI-based SE design. As a result, we obtained a complete set of theoretical and experimental data necessary for the development of “local” and distributed phase OFS based on SFMI and FPFI schemes. The results were also used for the development of OF hydrophones, accelerometers, tensometers, deformation and temperature gauges.

2.1. DISTRIBUTED AND EXTENDED OPTICAL FIBER SENSORS

A new trend of multiplexing different "local" gauges along extended measuring lines which were named distributed OFS became apparent in the late eighties of last century.

It has opened new opportunities for the effective solution of such problems as creation of the branched systems of telemetry connecting extended measuring lines to existing local or global OF communication links; OFS networking; reduction of MS costs.

Two basic MS schemes—distributed OFS (Figure 1b) and quasi-distributed OFS (Figure 1c) have been proposed. Both of them present significant interest in terms MS elaboration for monitoring such objects as shafts, bridges, tunnels, dams, landing strips, oil pipelines (OP). Measurement of OP parameters is performed continuously along the SE line in the distributed OFS, and in a number of separate points along the SE line in the quasi-distributed ones.

The main problem in the elaboration of such system is the development of a high-spatial-resolution system allowing multiplexing signals from separate local OFS or separate OFS sections. In our investigations, we used optical time domain reflectometry (OTDR) technique as a multiplexing method providing spatial resolution of up to 1 m. Distributed measuring lines for monitoring structural integrity of objects as well as their right-of-way have been developed from this principle. They present extended OF lines with a set of SE where external deformation results in the losses of guided light power due to OF bending caused by deformation or weight of the spotted object. Figure 3 presents a photo of such measuring line breadboard model with four SE intended for monitoring underground pipeline right-of-way. The maximum density of SE along the line is 200 units per kilometer, maximal length is 100 km, load threshold sensitivity 5 N.

As it was shown in our works, phase modulation of OF modes has integral character along the fiber line. It allows one to create extended OFS or extended OF measuring lines (OFML) with integral sensitivity.

We developed integral sensitivity OFML of various configurations based on SFMI scheme, and demonstrated their high sensitivity, long-term stability, ability to integrate influence of the deformation factors along the line, and opportunity of multichannel processing signals from different SFMI by using a single CCD matrix. It made SFMI-based

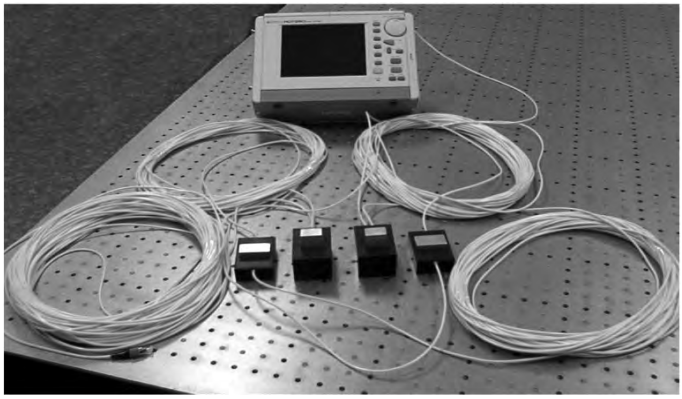

Figure 3. Extended fiber sensor for monitoring underground pipelines right-of-ways.

sensors perfectly suited for the development of distributed OFS of the tomography type.

Figure 4 presents an extended OF seismograph, consisting of 20 serially connected fiber optic accelerometers with sensitivity 1.4 mV·s^2/m and linear frequency response in the range of 8–400 Hz. An extended SFMI was used as an SE of an OF deformometer that was developed for research of microseismic crustal shiftings. The test results of the deformometer have shown the following specifications: threshold sensitivity—0.3 μm; dynamic range—25 dB; and frequency range—(0–100) Hz.

Due to small size and high flexibility of SFMI-based SE, they can be easily embedded into composite material objects such as concrete beams, without affecting their mechanical characteristics.

This fact was used for the development of sensor (its photo is presented in Figure 5) intended for monitoring concrete beams deformation under external loading both in static and dynamic modes. The results obtained proved that absolute axial elongation can be measured with an accuracy of 1 μm with the measurement range limited by fiber breakage only.

Figure 6 presents the results of the corresponding measurements. Curve *1* shows SFMI length variation inside the concrete beam under stretching and compression, curve *2* presents the results of elongation measurement by sensor signal processing. One can see that they are in good agreement within the limits of measurement error.

Figure 4. Extended OF seismograph.

Figure 5. Single-fiber multimode interferometer sensor for monitoring concrete beams deformation.

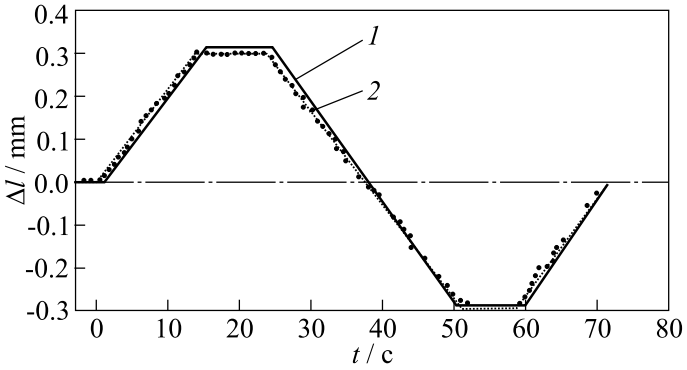

Figure 6. Time variation of beam length: *1*—micrometer measurement results, and *2*—results of SFMI sensor measurements.

3. Distributed Optical Fiber Measuring Networks

Distributed OF measuring networks (DOFMN) (Figure 7a) is the logical next step in the development of distributed OFS. Distributed OF measuring networks presenting a set of distributed OFS makes it possible to simultaneously measure parameters of PF in various two- or three-dimensional objects in real time, which is often a prerequisite for automatic inspection systems.

However, there are significant, and sometimes fundamental technical problems of multiplexing distributed OFS signals, problems of grouping large numbers of OFS resulting in low spatial resolution which makes it next to impossible to realize real-time measurements for high-accuracy reconstruction of PF distributions over extended areas or inside large objects.

So, a new promising approach for DOFMN design was proposed. It makes use of tomography principles applied to DOFMN, in terms of arranging the system of extended OFML according to a certain spatial topology (Figure 7b) (Kulchin, 2003).

Contrary to conventional distributed measuring networks, such DOFMN integrate the measurand signal along each OFML without singling out signals from distinct locations of the measuring line. Such an approach greatly simplifies either the measurement process and element base of the MS, which potentially allows one to increase the accuracy of reconstruction of PF parameters distributions, to decrease the costs of the system, and, finally, to overcome size limitations of distributed MS. The approach developed has allowed us to create a new class of measuring devices—DOFMN of tomographic type.

The development of the method being considered demands investigations into the processes of signal formation in individual extended OFML and grouped ones in DOFMN under the influence of scalar and vector PF, creating design methods for DOFMN with optimum topology taking into account the sort and character of PF under monitoring, developing classical tomography principles for the case of DOFMN signal processing, creation of special algorithms of processing large signal data files, etc. (Kulchin *et al*., 2000; Kulchin, 2003).

As a result of the researches carried out, it was shown that the amplitude of the integral signals of rectilinear extended OFML is a direct Radon transformation of scalar PF such as temperature, intensity

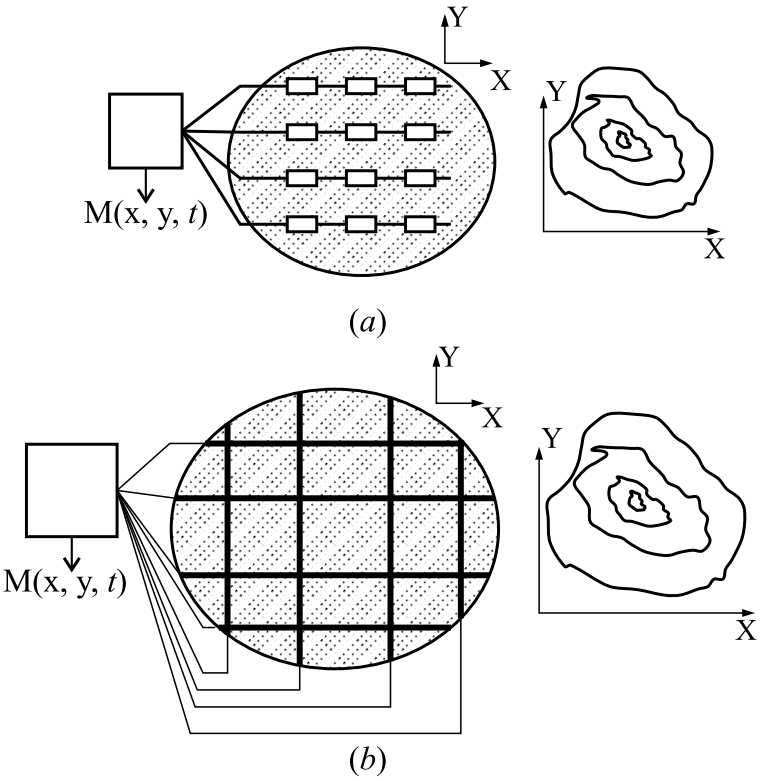

Figure 7. Fiber optic measurement networks: (*a*) network based on distributed OFS; and (*b*) tomography type network.

of mechanical vibration, and pressure. It has allowed us to apply the conclusions of the general tomography theory for the reconstruction of the originals of PF distribution functions using line-integral data.

The key principle was to monitor a PF by a network of OFML which enabled us to perform measurements in real time and to increase the DOFMN size.

Such an approach implies that a discrete number of integral images is used which demands transformation of the known reconstruction methods of the function originals for the case of line-integral data usage. The researches results showed that the ill-posed problem of reconstruction of a PF distribution lacking sufficient integral data set can be solved by choosing a quasi-solution with the minimal norm

deviation from the average value provided that the characteristic spatial frequency of the measuring network (which is given by $\Omega_c = \sqrt{6K/S}$, where K is the number of measuring lines in the network, S is the area of the network) exceeds the maximal spatial frequency of the PF under monitoring Ω_{max}.

Thus, DOFMN system based upon tomographic principles was for the fist time used for vector PF reconstruction.

The problem of tomography reconstruction of vector field distributions has no general solution. Therefore, the development of an original processing method for every new kind of dependence of the integral signal on PF parameters presents a unique fundamental physical and mathematical problem. This problem for various types of OFML has been investigated in works and methods of reduction of the problem to the previously solved standard tomographic task have been developed.

For the facilitation of tomographic DOFMN design, we developed various OFS capable of integration into extended measuring lines as well as of embedding into or attaching to the surface of the objects under monitoring. Figure 8 presents the theoretical and experimental results of DOFMN application to the reconstruction of both strain distribution potential component and transversal displacement squared gradient distribution over an elastic plate surface. The experimentally achieved correlation coefficients between the initial and reconstructed distributions (0.94) demonstrate excellent application prospects of DOFMN as a powerful tool for structural heath monitoring.

4. Distributed Optoelectronic Measuring Systems

Development of physical principles of adaptive distributed large-scale optoelectronic MS required setting up and solving the following problems:

- Fast and effective processing large data files
- Providing high-speed recognition and classification of reconstructed PF images and
- Development of methods of MS adaptation to the operation conditions.

For the solution of the above problems, we proposed that neuron computing technologies should be used for processing output DOFMN signals.

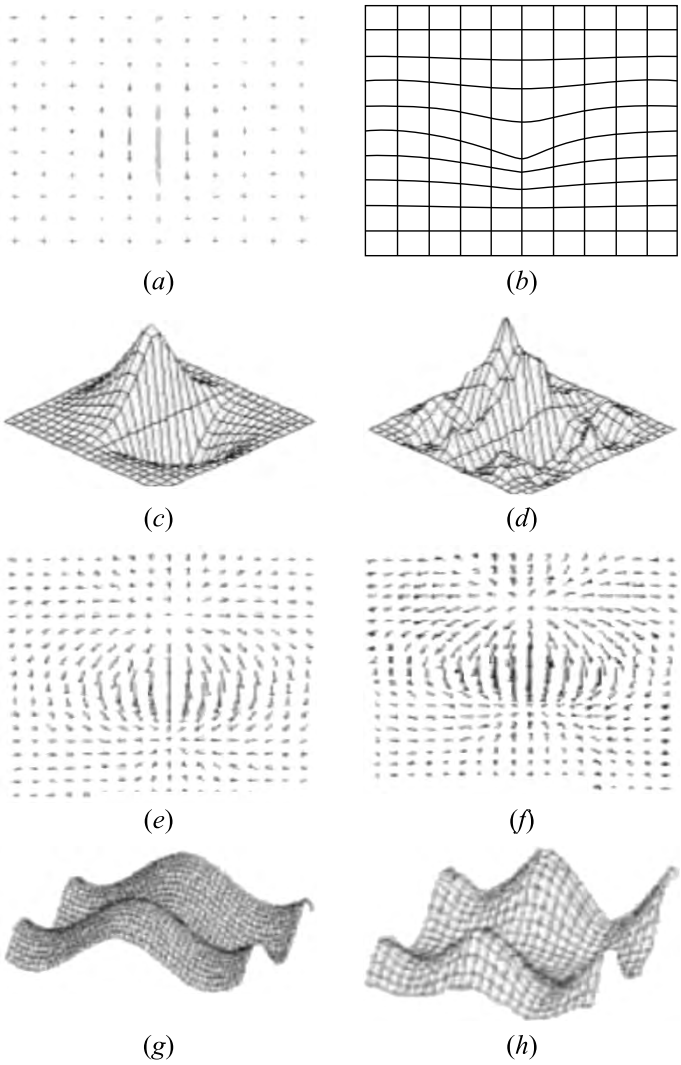

Figure 8. Results of DOFMN application to the reconstruction of both strain distribution potential component and transversal displacement squared gradient distribution over an elastic plate surface: (*a*) calculated distribution of vector field of longitudinal shears of elastic plate; (*b*) picture of deformed plate surface; (*c*) distribution of divergence of field of longitudinal shears of elastic plate: calculated, (*d*) reconstructed by DOFMN; distribution of potential component of field of longi-tudinal shears: (*e*) calculated, (*f*) reconstructed by DOFMN; distribution of square of gradient of longitudinal shears: (*g*) calculated, (*h*) reconstructed by DOFMN.

Neuron technologies allow a considerable increase of DOFMN operation speed along with such vitally important features as training ability, adaptability, signal classification capability, and external influence type recognition.

The efficiency of three-layer neuron networks such as perceptron has been proved theoretically and experimentally for processing signals of distributed OF MS.

Figure 9 presents a schematic of the tomographic DOFMN fabriccated on the basis of intersecting OFML. Every OFML presents an array of OF accelerometers. Such DOFMN allows processing output tomo-graphic data at a time of 25 ms. Measuring system was developed to carry out the following operations: classification of objects, determination of their spatial coordinates, as well as speed and movement direction.

Figure 10a represents a one-dimensional SFMI-based tomographic system of registration of static deformation. The system allows one to reconstruct transversal deformation distribution over an extended one-dimensional object (such as beams, girder, etc.). That is illustrated by the results depicted in Figure 10b. Along with practical applications, this MS can be used in theoretical researches, for example, for modeling biological object behavior.

As it was shown, the combination of neuron computing technologies with fuzzy logic approaches opens up exciting opportunities for further development of distributed optoelectronic MS.

(*a*) (*b*)

Figure 9. Distributed optical fiber measuring network of square of 100 × 100 m: (*a*) fragment of DOFMN; and (*b*) control instrument panel.

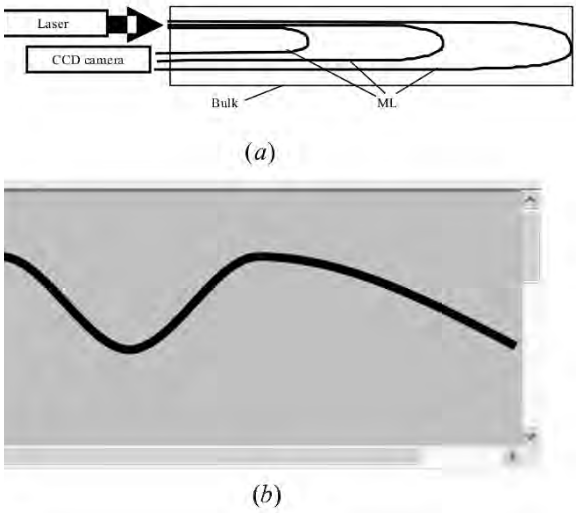

Figure 10. One-dimensional tomography system for monitoring deformation effects: (*a*) scheme; and (*b*) one of reconstructed profiles of transversal shifts of the beam under loading.

5. Concluding Remarks

Thus, the researches carried out offer in-depth understanding of the physical and technological aspects of distributed optoelectronic MS intended for measurement, modeling, and control of various PF and objects. Performance characteristics of integral sensitivity extended OFS and OFS-based measuring networks are reviewed along with the prospects and most rational technical solution dealing with their design.

Despite apparent clearness and understanding of principles of such measuring and control systems, there are many problems on the way to their large-scale practical application. Top-priorities among them are the following:

- Development of methods of distributed optoelectronic MS dimensional scaling
- Further improvement of neuron-computing algorithms for MS signal processing, based upon optimization of neuron layer number, development of new methods and criteria of neuron network training, and application of fuzzy logic apparatus

- Development of effective methods for performance stabilization of distributed optoelectronic measuring lines and systems and
- Development of new SE physical principles and technological concepts based on nanotechnology.

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THEME 6

EMERGENCY RESPONSE PLANNING

Collage by Igor Lukashevich

HOW TO PLAN FOR EMERGENCY AND DISASTER RESPONSE OPERATIONS IN VIEW OF STRUCTURAL RISK REDUCTION

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Abstract: Increase of economic activity, population density, choke points by multiple use of space, traffic nodes (mega-storey) high-rises etc. make our society more vulnerable. At the same time, there is a trend of increase in safety standard with political consequences. A disaster plan shall be ready and the mayor of a city is held responsible. It calls for a new multidisciplinary approach of emergency and disaster response planning coping with a wide variety of threats. It starts with the dilemma, in particular for political leadership, of where to draw the line of 'how safe is safe enough.' This depends on ambition of governance, risk profile of the region, policy of what shall be the capacity of emergency and disaster response forces versus the industry effort in protection and that of the public itself. Land use planning and licensing of industrial and building activity are keys for timely preparation. Risk analysis is used for years as a basis for decision making despite the uncertainty in underlying models. For the new task, however, not only space but also explicit time resolved scenario analysis has to be introduced since time is in response

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effectiveness a crucial parameter. The paper will describe a possible way ahead to help stakeholders to reach their goal, and the various tools, models and data needed. In the complexity of modern urban area and associated organizational structure scenario analysis once fully developed can become a major tool for improving resilience.

Keywords: emergency response; disaster response; scenario analysis; land use planning; urban area; fire brigade; emergency medical system (EMS); incident

1. Introduction

1.1. GENERAL

Local authorities are responsible for the (first) response to incidents and disasters within their territorial/regional boundaries. As a corollary local emergency and disaster response services have to be prepared for all types and levels of incidents and disasters that may result from the risk profile of the region, be it of natural or cultural/anthropogenic origin. A risk inventory is drafted to decide on risk sources that: can be handled—are controllable—with ease, and where control is doubtful and is clearly absent. For the last category emergency and disaster response services have the choice to increase their operational strength, or reduce the risks and hazards of the risk source (risk prevention). Generally it is more efficient to reduce the risks then to increase the response strength, but the position of emergency and disaster response services in risk reduction is not well defined. Their interest in risk prevention is primarily with the risks that remain after licenses have been granted for risk producing industrial activity, for the traffic and transport infrastructure, and for the construction of dwellings and high-rise office buildings and other urban megastructures with potential high risk exposure. Emergency and disaster response services are confronted with the remaining risks in the form of an array of possible incident scenarios. Their effort will determine to considerable extent the final outcome of incident scenarios that come to expression. In case an incident occurs or disaster strikes the services are judged in the final analysis on their success or failure to save victims that would have become

casualties otherwise, as well as by the extent of control over the incident development and by the ability to prevent damage.

In view of their responsibilities, it seems logical that emergency and disaster response service have a say in licensing decisions. This indeed is the case in several instances. For process industries the Post-Seveso and Integrated Pollution Prevention and Control (IPPC) EC Directives[1] make this very clear, as do the building codes in most countries. Emergency and disaster response services generally fill in their role by putting specific demands on a very detailed level such as for emergency exits, fire hydrants, sprinkler systems etc. They are, in other words, accustomed to prescriptive rules and regulations in a deterministic approach. They are less acquainted with risk-based or performance-based design, as, e.g., described by Purser (2000). This is, however, not only a matter of custom, but also of limited knowledge. Not only are there knowledge gaps concerning the effectiveness of preventive measures, also the performance of disaster response itself has not yet been measured in a scientifically based, standardized manner (see, e.g., Sundnes and Birnbaum, 2003). As a consequence, it is to date not well possible to quantify the contribution of emergency and disaster responses to the (reduction of the) risk-level. The question of the contribution to risk reduction of emergency and disaster response and how it may be influenced, is the subject of this article.

The contribution of emergency and disaster response to lower the risk level may be elaborated in two complementary ways:

1. One may start with the overall risk profile of a region as a starting point and try to determine what strength is required to deal with that risk profile.
2. Once the response strength has been determined, one may take this as a starting point, and see to it that the available response force may be deployed to its full extent anytime and anywhere in the region. This implies that the ambient and interior settings of specific risk objects have to be adjusted to the available response strength, among which in the urban environment are crowded areas such as a stadium, railway station, airline terminal or shopping mall.

[1]Post-Seveso Council Directive 82/501, amendments 87/216 and 88/610 and the second version Seveso II, 96/82/EC, of 9 December 1996, and IPPC Council Directive 96/61/EC, adopted at 24 September 1996.

(Ad 1) To answer the first question the risk level of a region has to be translated into a strength of the response forces. Logically a criterion for tolerable risk shall be used to answer this question, as the risk level is conditional to the choice of a suitable response level. However, the use of risk criteria to date has been limited mostly to single risk sources in terms of expected fatalities in the public. Criteria for aggregated risk for a region as a whole are not available. It is a challenge to risk analysts to come up with such a criterion, which, however, is beyond the scope of the present paper, although partly the need for data and other information will be identified. However, even if the analysis could be done perfectly, in the final decision making, it will still be a matter of governance ambition to choose a level of an economically affordable and societal accountable response-strength for the emergency and disaster response services.

(Ad 2) To answer the second question, the conditions for emergency and disaster response on the scene for specific risk sources have to be translated into space and time requirements. To answer this question logically, a response criterion will be needed, since the response needs are conditional to the specific risk and local settings. However, to date such criterion have not been formulated, and response assessment methods have not been formalized. This article will focus on how in planning processes and dialogue between stake holders this matter could be handled and what information is lacking.

Except for the military, this kind of questions has never been posed very explicitly, at least not in the Netherlands, until the disaster response services became more professional by the end of the last century. The emergent threat of terroristic attack, the recent step-up of multiple-use of space and underground structures, the expected increase of transportation of hazardous materials and the recent obligation for the city mayor to sign (operational) disaster response plans, further added to the feeling of urgency.

1.2. STARTING POINT FOR URBAN PLANNING: GROUP RISK DILEMMA

In the Netherlands, risk to the population at large by industrial activity involving hazardous materials is bound by two standards: the individual risk standard and the societal or group risk standard as a measure for societal disruption. The first is also called location bound risk,

since it is a risk a person is subjected to at a certain location with respect to the threatening activity. Individual risk is expressed as the probability per year of an exposed person to get killed (as a direct consequence of the event) and can be shown as iso-risk ground contours around an installation, see Figure 1. The individual risk level shall remain lower than 10^{-6}/year. It means that the 10^{-6} probability contour around the activity should remain outside inhabited areas and areas with otherwise vulnerable occupants, such as day care centers, schools, nursing homes and hospitals. The group risk is expressed as a (cumulative) probability of 10 or more fatalities among neighboring inhabitants (incl. vulnerable groups in, e.g., hospitals, schools, offices and hotels in the vicinity, but not workers or passers-by in the traffic external of the site). The value should stay lower than 10^{-5}/year for 10 or more fatalities, or lower than 10^{-7}/year in case of 100 or more, etc. The individual risk standard is compelling. The group risk standard may be waived if sufficient grounds are present(ed). These are amongst others high economic interest and sufficient means for emergency and disaster response measures. The fire brigade got by law the task to advice on waivers and see to it that sufficient means for emergency and disaster response are present. Such waivers may apply to land use plans, license applications for industrial activities, routing of hazardous

Figure 1. Classical example of iso-risk contours of individual risk around a particular part of an installation according to a specific scenario. Outer contour represents probability of being killed of 10^{-8}/year, most inner circle 10^{-5}/year.

materials transports, or the expansion of an urban settlement in the direction of an existing industrial site or transport activity. This role is a relatively new addition (since 2004) to the traditional role of the fire brigade for advising on building licenses, ranging from high rise buildings to underground tunnels and stations.

The methodology for determining risk levels of activities with hazardous substances is standardized to a large extent. A number of manuals has been developed, the so called colored books (Yellow—releases, Green—damage, and Purple—basic scenarios and probabilities). Mostly, consultants perform risk calculations with a strongly recommended/prescribed computer model. By and large this (probabilistic) way of thinking has pervaded the various regulatory bodies that have to deal with chemical risks. It also holds for other types of risk, such as traffic and flooding (see, e.g., dissertation Jonkman, 2007).

A methodology to determine the necessary regional strength of emergency and disaster response force and to optimize the conditions for response has not well developed yet. In the Netherlands the response force to date has to be matched with fixed templates of maximum disasters for 18 disaster types considered realistic in a region.[2] This, however, is not feasible. Fire brigades have trouble answering the questions of the competent authority on the acceptability of exceeding the group risk norm at a specific location with their general guideline tools for the region as a whole. Recently though, a methodology to optimize conditions for response has been developed for tunnel safety.[3]

Classical risk analysis, as performed for determining individual and group risk, is no solution for fire brigades. As there is only one response organization in place, it has to respond to all scenarios possible in the region. Because of the large number it is not an option to prepare for every possible scenario separately. Instead, the challenge of emergency and disaster response planning is to find common deno-

[2]There are Ministerial Guidelines available to perform the necessary calculations. In Dutch: *Leidraad maatramp* and *Leidraad operationele prestaties*, Ministry of Internal Affairs, 2000 resp. 2001. The Netherlands is subdivided in 25 safety regions.

[3]The method is described in a guideline for scenario-analysis for road and rail tunnels (two parts). In Dutch: Leidraad scenarioanalyse ongevallen in tunnels: deel 1: wegtunnels; deel 2: spoor-, tram-, metrotunnels en overkappingen. Center for Underground Building (COB), 2004, resp. 2006.

minators among the scenarios and to typify the complete set by just a few selected ones. These selected scenarios are used to test the organizational strengths and weaknesses, and may be viewed as *calibrating scenarios*. The other side of this coin is that each selected scenario has to be analyzed in depth. Each individual incident scenario is assessed over time as are the processes of self-rescue and emergency and disaster response. The assessment focuses on the time/space-factors of these processes and on measures to improve them. This combination of requirements for assessing response effectiveness has led to the term *scenario analysis*.[4]

The differences in approach between risk analysis and scenario analysis produce frictions in the decision making process, since they have no common denominator, e.g., how to compare a risk level with a control level of a scenario. On one hand, the technocratic approach of risk analysis is challenged by policy, social arguments and emotion. On the other hand, the fire brigades are challenged to come up with mature methods and test criteria for scenario analysis. In the following an avenue for future development is shown which in due course could alleviate this situation.

2. General Concepts

2.1. CONTROL OF INDIRECT DEATHS

The goals and objectives of disaster response have not been precisely formulated to date, but are intuitively clear. It boils down to saving lives, limiting damages and restoring public order and daily life. To

[4]Scenario is a possible chain of events related to the system under consideration, following a usually rare, initiating event accompanied by violent, life threatening effects as explosion, fire and toxic release. Depending on the definition, the scenario may include — apart from the source term and effect conditions — also the exposure and vulnerability situation. It will model as well the response potential at any given moment in time. In scenario analysis time processes determine the final result: at what time does the fire brigade arrive, how long does it take to get the fire out etc.? Risk analysis as e.g. applied for land use planning is performed on the basis of all imaginable scenarios. Time is implicit. In that case the probability of occurrence and the extent of effects is the essence for decision making. In fact the two are members of the same family.

what extent it is useful to organize emergency and disaster response for limiting material damages may be assessed rather straightforward with cost-benefit analysis. For the response activities that regard human life it is less straightforward to strike a balance between needs and means. A normative approach is required to specify to what extent human life should be preserved in the course of a disaster. The question how many casualties/victims should be saved by the responders is not easily answered. It is just another version of the question 'how safe is safe enough'. Of course it is possible to translate the emergency and disaster response strength into a number of lives that may be saved, but it is not feasible to make policy makers state publicly that this is enough and that you may let the remaining victims die. This is also contradictory to the nature of emergency and disaster response, that is called into existence as a backup system for dealing with mishaps and eventualities of any nature and magnitude. The simplest—and probably best—way to answer the question is to state that everybody who still has a chance to survive after the first blow should be saved. This, however, has a limit of affordability. We should prepare for scenarios that are still more or less likely to occur. It is not useful to spend public funds to prepare for highly improbable scenarios. It then becomes a matter of defining the maximum scenario, that is still considered to be realistic, that may serve to determine the required response strength. Here, we get into the discussion what is considered realistic and what threshold of incident frequency shall be set.

There seems to be no uniform answer to this issue. The realistic probability threshold seems to vary by incident type. Risks of road traffic are, e.g., dominated by crashes of individual cars occurring rather frequently, so it may suffice to prepare for the once in a lifetime car chain mega-collision or a bus crash. The risks of hazardous materials on the other hand are dominated by low probability but high consequence events, so it may be worthwhile to prepare for a once in a million year incident. As stated before, it obviously is a matter of policy to choose probability levels, that serve as guidance for the capacity planning of response services.

For immediate fatalities, nothing can be done anymore, but additional—secondary—fatalities should be avoided as much as possible. Here, secondary deaths are defined in relation to the response processes at the scene. Two types of avoidable fatalities are distinguished:

1. Those, who can rescue themselves and the extent they are successful
2. Those, who need to be hospitalised and the extent they arrive in hospital in time.

(Ad 1) The self-rescue potential is analysed by combining a scenario with an evacuation or escape model and/or a model for calculating the protection level that structures offer when taking shelter. The objective of the analysis is to see whether unfavourable or even untenable conditions may occur while victims are still caught on the spot. If this occurs it means self-rescue is hampered or has come to a halt and those present fall prey to the further development of the incident and may loose their lives, such as with an expanding fire.

(Ad 2) Hospitalisation is assessed by the timeliness of medical assistance, traditionally called the *doctor's delay*. This is a *pars pro toto*, because before medical assistance can be provided to trauma victims, many other activities have to be undertaken. Disaster response is teamwork. More in particular, the police must have been successful in clearing the roads, responders must have been able to gain access to the scene, and the rescue teams must have been able to free the ones caught and bring the trauma victims to medical responders before medical assistance can start. By measuring the performance[5] of the medical teams, one therefore measures the performance of the foregoing activities by other responders such as police and fire brigade as well.

Emergency and response services try to save lives and thus prevent secondary deaths, but what does this mean for risk acceptance? Should secondary deaths, e.g., be added to the risk norms? The answer to the last suggestion is: no! The objective of a risk standard is to put a certain restriction to economic activities which entail hazard. The objective of a scenario standard is different. A scenario standard purports to set conditions for emergency and disaster response. The objective is not acceptability of the risk per se, but controllability of the resulting (remaining) scenarios given the local setting for the responders. Of course this does not withstand it may be wise to reassess a preliminary

[5]The performance of medical assistance is classically measured in terms of numbers of (initially, respectively definitively) stabilized victims over time.

conclusion of a risk level being acceptable in case the subsequent scenario analysis is showing the result is a rather low level of control!

2.2. HADDON'S MATRIX

The role of emergency and response services in risk prevention is still in development. A working model to identify the relevant risk factors may be useful. The matrix presented by Sir William Haddon (Haddon, 1972) for road traffic safety in the UK is probably the most well known and best accepted model,[6] see Table 1. The matrix has been generalized by the WHO for the purposes of injury surveillance (Holder *et al.*, 2001). The matrix is based on the concept that all system-parts may contribute to risks and safety in all phases of an incident or disaster. It is composed of conditions of the host (the exposed), properties of the vector (the threat), the physical and the socioeconomic environment. The term 'event' is used, meaning the physical effects initiating the incident. Three event phases are distinguished: before, during and after the event. Risk factors that become operative in, e.g., the event phase are not effective in preventing an incident, but may be helpful in limiting the consequences of the incident and in promoting the response at the scene.

In incident management, the focus is on the incident, i.e., the event phase. Traditionally the event phase has been addressed only in operational terms: What can we do, given the situation at hand? Today the preventive aspects of the event phase come more into perspective as well: What can be done on the forehand to improve the controllability of an incident-situation? The postevent phase, or aftercare management, to date has received little attention. In this article it is not possible either to pay attention to this phase, although the importance of preventive measures for this phase are recognized as such.

Emergency and disaster response services are well trained to identify the risk factors in the event phase, but are less accustomed to advise about the preevent and postevent phase. Risk analysts have more expertise about risk factors in the preevent phase and injury prevention

[6]Although traditionally in The Netherlands the safety chain of pro-action, prevention, preparation, repression and after-care has been used.

TABLE 1. Haddon's matrix generalized by the World Health Organization (Holder *et al*., 2001)

1.	**2. Host**	**3. Vector**	**4. Physical environment**	**5. Socioeconomic environment**
6. Pre-event	7. Is host predisposed or overexposed to risk?	8. Is vector hazardous?	9. Is environment hazardous? 10. Does it have hazard reduction features?	11. Does environment encourage or discourage risk-taking and hazard?
12. Event	13. Is host able to tolerate force or energy transfer?	14. Does vector provide protection?	15. Does environment contribute to injury during event?	16. Does environment contribute to injury during event?
17. Post-event	18. How severe is the trauma or harm?	19. Does vector contribute to trauma?	20. Does environment add to the trauma after the event?	21. Does environment contribute to recovery?

researchers have more expertise about the risk factors in the postevent phase. Consequently the emergency and disaster response services will generally limit their advice to the event phase. Nevertheless, they may define requirements of the preevent phase in functional terms, regarding, e.g., the failure on demand of a certain activity.

2.3. LAYERS OF PROTECTION CONCEPT

The objective of scenario analysis is to identify relevant risk factors and potential countermeasures. To be able to identify the risk factors in a systematic manner the concept of layers of protection may be useful. This concept has been developed in nuclear reactor safety engineering in the 1970s and is based on defining separate systems each

consisting of technical and procedural components, sometimes with man-in-the-loop but often fully automated, which function fully independently. In case unfavorable conditions arise the layers start acting in sequential order. Consecutive layers come into action when conditions escalate and previous layers do not achieve the desired effect.

The layers may be active in the sense that they have to be activated by some manual or automatic mechanism such as pressure relief and sprinklers activated by sensors, but also passive layers exist to mitigate effects, such as walls, dikes and keeping distance. In Figure 2, an example of generic layers for a chemical process is presented with layers as an onion around the source coming into action from inside out. The concept has become rather wide-spread in the chemical industry over the last 10 years. The first four layers in Figure 2, up to and including automatic action, SIS—Safety Instrumented System or ESD—Emergency Shut-Down, can be called preevent phase layers. All further layers are event phase layers. The layers up to and including possible plant/company emergency response is the responsibility of the site owner. In Figure 2, one can note the last or outer layer of community emergency response. This will come into action after the internal company fire brigade runs out of the 15 minute which are (at least in the Netherlands) allotted to them to get the incident under control. Postevent phase layers, related to the aftercare, are not included in the model, and will not be taken into consideration here.

In Figure 3, the aspects that are important for emergency and disaster response are elaborated. The event phases are depicted on the vertical axis and the layers are rephrased in general terms after their function with respect to three zones:

1. The risk source, buildings and structures at the site
2. The (urban) open area around the site
3. Buildings and structures in the potentially affected area external of the site.

(Ad 1) The layers of protection for the risk source and structures at the site acting in the preevent phase are the same as in Figure 2, but the event phase layers are adapted in Figure 3. From this, the advisory role of emergency and disaster services becomes clear. They may demand for the preevent phase in general terms a certain level of inherently safer design from the owner and a certain level (and layering) of

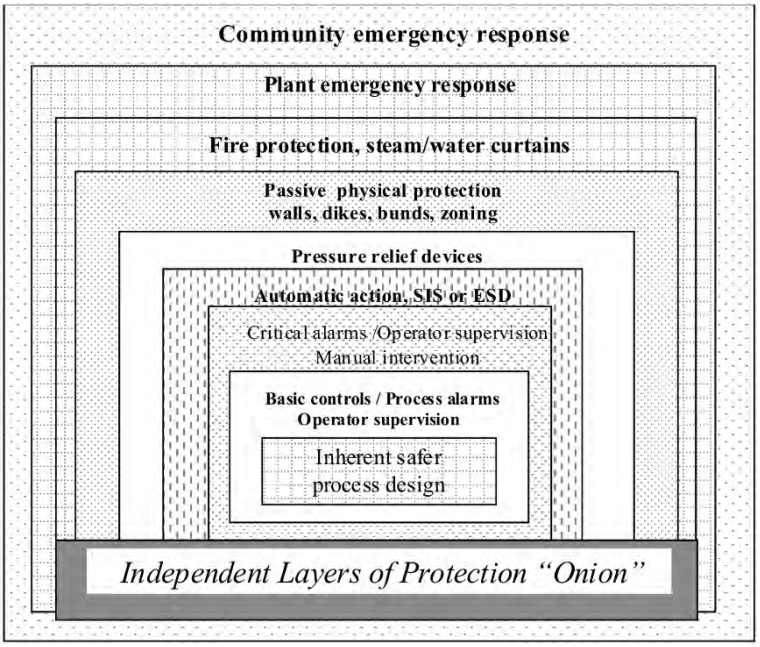

Figure 2. Layers of protection concept as introduced by the Centre for Chemical Process Safety of the American Institute of Chemical Engineers, for chemical plant in the mid nineties (SIS—Safety Instrumented System or ESD—Emergency Shut-Down).

safe operations from the operator. In more detail, the services will address, however, the protection layers of the event phase to limit off-site consequences, to promote self-rescue of personnel and to optimize the conditions for the (private and public) first response at a site.

(Ad 2 & 3) In Figure 3, layers of protection have been added for the off-site environment and building structures where people may reside. Such layers of protection are by definition limited to off-site emergencies, i.e., to situations for which it is physically not possible to curb the source and control the incident within site limits. The layers acting in the event phase mostly serve to 'buy time' for self-rescuers and responders. Examples related to spatial planning are the presence of fire water basins, stopping lines and buffer zones for city fires, routes for approach and access of responder vehicles and ample parking space near the scene to run the operation from. Examples related to building

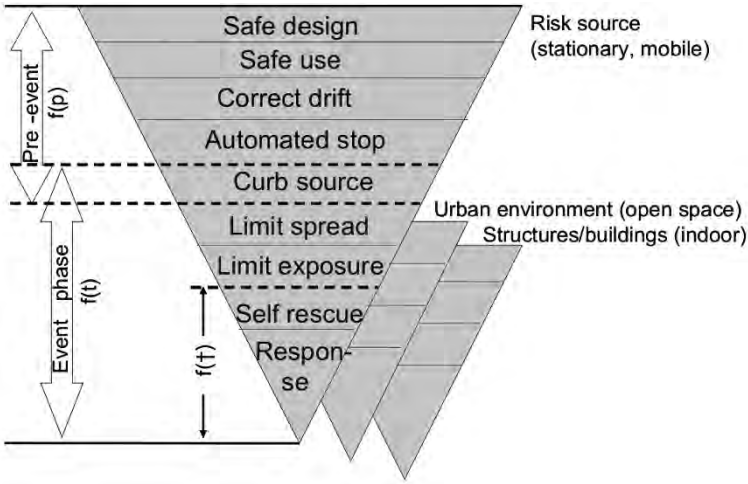

Figure 3. Layers of protection characterised for emergency and disaster response analyses. The layers are specified by their function and the time of functioning. Layers are not restricted to the risk source, but also include the build-up area around the site and the building structures in the neighbourhood.

structures are sprinklers on the outer wall and safety glass in the outer windows, means to shut off the ventilation, and emergency routers and exits.

Self-rescue and emergency/disaster response are the last and—therewith—least effective layers, they are 'end of pipe.' Self-rescue is of a higher priority than emergency/disaster response, since the potential gain is larger. Being 'end of pipe' implies that it generally pays to invest in higher protection layers instead. At the same time, failure of self-rescue and emergency/disaster response layers will directly result in trauma and fatalities. Being 'end of pipe' also implies that it is not anymore a matter of buying time, but of 'buying' lives. Therefore it is useful to assess the consequences of a scenario in terms of the success of self-rescue and of emergency and disaster response.

Risk analysis to date has focused on the risk source itself and on safety distances and less on the whole of measures of risk control. The latter is more complex, since there are different parties involved with different responsibilities. Yet, it is the essence of the responsibility of public authorities to push for solutions with all parties participating in the debate and considering all possibilities. The concept of layers

of protection analysis looks promising as a tool to assess such risks. Emergency and disaster response services may determine whether they can cope with the work load of selected scenarios. This may help in the dialogue with the site owner and operator to decide about sufficeency of measures.

3. Position and Use of Scenario Analysis in Decision Making

3.1. POSITION OF SCENARIO ANALYSIS

Decision making for safety purposes is a stepwise process. In the final analysis, one formally decides on a package of safety measures, but in practice the process is much more incremental. For one, rules and regulations need to be fulfilled, with, e.g., a number of basic measures, such as in the European legislation for (to date only road) tunnels (2004/54/EC). Rules and regulations may in addition pose performance requirements, such as a maximum accepted risk level and a minimum scenario control level for emergency and disaster response. A risk level may be assessed with a Quantitative Risk Analysis (QRA), and a scenario control level may be assessed with a scenario analysis, but the relationship between these two assessments is still undefined. In this paper the position is taken that both a QRA and a scenario analysis are needed to gain sufficient insight in the safety situation of a given situation in the context of emergency response. A QRA results in a first global estimate of the general safety situation for the neighbor-hood, whereas a scenario analysis gives more detailed insight in the local situation and consequences for all potential victims both at the site, e.g., workers and externally in the public at large. The two assessments are complementary, as are the resulting proposals for measure packages. How to decide on a total package of measures is still undetermined, but in this paper as set out in the previous section, it is proposed to follow the rules of the layer of protection analysis in this respect (Figure 4).

3.2. USE OF SCENARIO ANALYSIS IN EMERGENCY AND DISASTER MANAGEMENT

Emergency and disaster response services may wish to perform scenario analyses for different purposes:

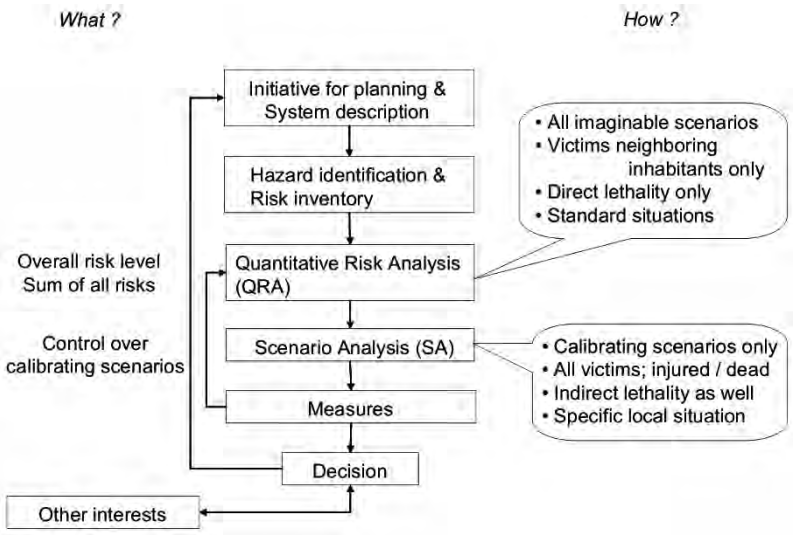

Figure 4. Decision-making process for the purpose of urban area safety.

- For preventive purposes in case of licensing as purported in this article
- For preparative purposes of operational plans
- For repressive purposes of responders.

One use is not the other. Of course, some aspects are the same for all types of use such as the need to assess the number of victims, but the level of detail and the assessment criteria vary widely.

(Ad 1) For decisions on land use planning, safety licenses, and the choice of transport routes for hazardous materials, rather detailed and well standardised scenario analyses are required. The objective of an analysis is to set the strength of the consecutive layers of protection. The results need to be well underpinned, since there may be discussion about who shall be charged for the required investments: the owner of the risk source or the community. The results shall be assessed in a normative way. A standard is best formulated in terms of a threshold value of zero secondary deaths, see before Section 2.1. Less protection will increase the likelihood of the occurrence of secondary deaths. Such procedure will put the burden of proof on the one claiming that a projected level of protection will not lead to secondary deaths.

(Ad 2) Scenario analysis may also be done to support operational plans for specific risk sources or *hot spots* such as a stadium or a railway station. The analysis may serve to prepare and train disaster responders for what to expect on the scene. Due to lack of data a detailed prediction of numbers of victims is not well possible yet. On the other hand, since operational degrees of freedom are rather limited detailed analyses are not really needed for operational purposes. Only if major operational consequences are at stake, such as magnitude of the first response (e.g., one or all available vehicles), types of responders needed (e.g., ± HazMat teams), availability of access roads (e.g., instructions how to open the gate) and decision about area evacuation, then a more detailed scenario for operational purpose may be valuable. Probably the most difficult task is to resist the forever continuing political pressure to come up with a number of victims to be expected. To that end a three-stage procedure is advised:

Step 1. Pro-active and preventive scenario analysis shall lead in principle to adequate risk control up to the given ambition level.

Step 2. If necessary an operational plan is drafted. Control of the incident can already be assumed and is therefore starting point. Hence, the plan can be focused on attack strategy and extent of responder deployment.

Step 3. If the disaster management plan calls for additional preventive measures, these shall be included in the revision licenses.

(Ad 3) In case a disaster occurs, immediate action is required even though the amount of information is very limited in first instance. Scenario analysis may be helpful for repressive purposes to support the assessment of initial situation assessment. For example, the dispersion of a toxic cloud may be modeled to give an idea about the extent people get exposed, to what extent it is possible to keep shelter in place and what are the consequences of an evacuation? Many services have such models available, but most are hesitant to use them in practice. Anyway, the added value of such models is mostly determined by the possibilities to incorporate feed back from the field in the model, such as infrared images of a fire and health complaints in the far field (e.g., relayed by telephone).

3.3. PROCESS OF SCENARIO ANALYSIS

The process of a scenario analysis is different from that of a quantitative risk analysis. For the latter, computational tools are available and national standards are established, so that the analysis is more or less purely computational, and often done by outside consultants. Scenario analyses on the contrary are generally performed by experts from the interested parties themselves. The value of the exercise originates to a large extent from the common understanding gained of the situation at hand by all parties involved. This can be achieved by working together stepwise through all problems that pop up during an incident. Generally, consensus can be achieved on solutions that are classed worthwhile, not worthwhile, or need to be investigated further. As a consequence, much emphasis is put on the orderly conduction of the analysis process. In general the process steps are the following:

- Compose a scenario analysis team
- Decide about the assessment framework
- Execute the analysis
- Agree on preferred measures on a technical level
- Take decisions on executive level by the competent authority and assure implementation

(Ad 1) Putting the analysis team together is the first and maybe the most important step. All stakeholders shall be represented.[7] From the side of the competent authority, these are: spatial planning, safety licensing and emergency and disaster response. As shown in Figure 5, these services have many interfaces. However, communication between them is not assured, since they are generally divided over different authorities, e.g., in the Netherlands: municipality, province respectively thesafety region. A common policy document on safety for all three services and authorities together might be helpful (see ad 2).

[7] If the number of stakeholders is high, e.g. with larger projects such as an industry park or a traffic tunnel, it may be worthwhile to install a safety committee where all parties are represented, and to limit the scenario analysis team to experts of the most directly involved parties.

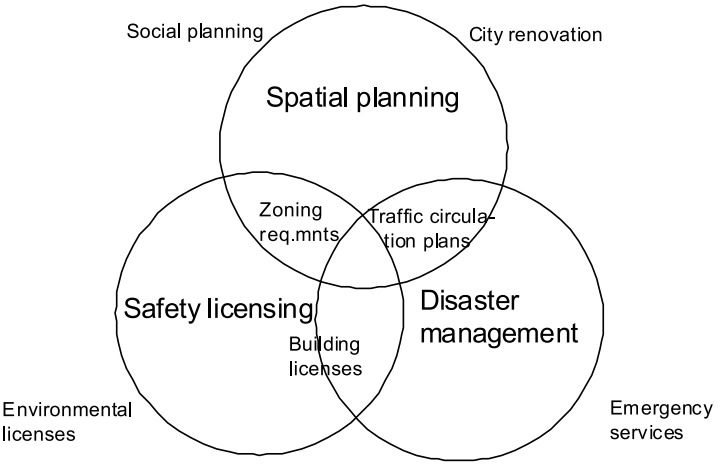

Figure 5. Interfaces between the advising bodies representing the competent authority with respect to urban build-up area in particular at the pro-action and prevention stages.

(Ad 2) Other than for risk analysis, in scenario analysis methods and standards are only partly established. A national framework is not available yet. It is therefore essential to agree beforehand on decision criteria and on an analytical framework and to have this formalized by the competent authority. In particular, one should formalize the scenario selection, choice of computational models, rules of thumb for consequences of damage mechanisms that cannot be modeled yet, and decision criteria.

TABLE 2. Components of a scenario analysis.

1. Description of system
2. Identification of hazards, inventory of incidents, data bases
3. Selection of scenarios
4. Analysis of consequences: explosion, fire, toxic cloud incl. smoke
5. Selection of measures, layers of protection

(Ad 3) A scenario analysis consists of a number of components, as summarized in Table 2, partly illustrated in Figure 4 and treated later (in Section 4).

The analysis follows the incident process step by step. Self-rescue and emergency response are examined step by step for excessive time requirement and capacity bottle necks. Measures and provisions are

identified that may keep the required time as short as possible and bring the capacity for all steps on the same level.

Self-rescue steps are dependent on whether it is an open air or an indoor scenario. In the most extensive form first evacuation of the building and subsequently area evacuation may be at hand. More in general, the following steps may be distinguished: wake-up, coming in action, escape, crossover to a safe area, follow-up transport.

For emergency response, the steps are: report coming in, alarm of first responders, turning out of the service post, arriving at site, lining up, reconnaissance, access to the scene, operations at the scene, transport of victims. Up to the reconnaissance, the steps are generic and may be treated for all emergency and disaster response services together (fire brigade, police, medical assistance). Reconnaissance and the following steps are task dependent and need to be treated separately.

(Ad 4 & 5) The scenario analysis team is positioned centrally in the analysis and operates independently within the established assessment framework. The decision making process is staged. First, agreement is sought at technical level about a package of preferred measures and provisions. The proposed package and remaining points of discussion are presented to the policy makers for a decision.

4. Components of Scenario Analysis

4.1. SCENARIO DEFINITION

Scenario analysis is performed in many policy areas, such as economy, demography, and politics. Generally, the aim is to sketch a possible future development. Since prediction of future trends is full of uncertainty usually a high, middle and low intensity scenario are presented. In scenario analysis for emergency and disaster response, however, the interest is not in the uncertain outcome of a certain future, but in the uncertain outcome of an uncertain disastrous event some time in the future. Here, scenario analysis serves to gain insight in the possible developments of an incident in time. The results may—as stated—be used to define the coping capacity of the emergency and disaster response services and to identify the local conditions needed to deploy the disaster response to its full potential.

A scenario analysis consists of several components (this section) and steps (see Section 3.2). The components of a scenario and a scenario analysis are presented in Figure 6.

A scenario is defined by a source term (Loss of Containment of a hazardous substance, LOC), meteorological conditions, presence of people, vulnerability of the exposed groups and response potential. Logically maximum realistic assumptions are made for all these (input) variables, although sometimes the maximum realistic assumptions are limited to the source term and meteorological conditions and average assumptions are made for the remainder of the scenario. This last practice may be wise for quantitative risk assessments, but is not suitable

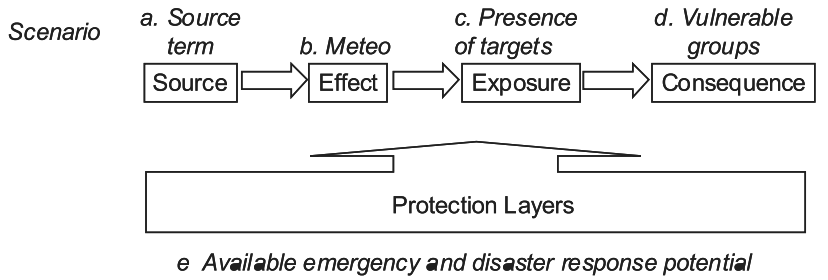

Figure 6. Components of a scenario (*a–e*) and of a scenario analysis.

for scenario analysis, since it maximizes fire fighting and other types of source control whereas it averages the victim oriented tasks.

Source terms have to be determined for all relevant damage mechanism by hazard identification methods (Section 4.2).

Stable meteorological conditions are generally selected for a scenario, e.g., in the Netherlands Pasquill class D5 or F2. The meteorological conditions are input to (physical) effect models (Section 4.3).

The presence of people is characterized by density and typical pattern of activity/occupation; e.g., commuter public, shopping public and holiday public for a train/subway station. Among the people in the affected area there may be vulnerable groups, either in transport or residential, in a nursing home, hospital, kindergartens, school, swimming pool etc. The presence and vulnerability of people are input to damage models, which in turn have to be linked to evacuation models and emergency and disaster response models to perform a consequence analysis (Section 4.3).

Available emergency and disaster response potential has been added to the definition of a scenario, because the capacity of the services varies widely over time. During evening and night time, in weekends and holidays staff levels are relatively low. Further, during rush hours it takes relatively much time to approach a scene due to traffic jams, and after a regular operation program has been executed, there are hardly any Intensive Care (IC) beds in the hospitals left.

4.2. HAZARD IDENTIFICATION

Quantitative risk analysis and scenario analysis are two members of a large family of risk assessment methods (see, e.g., PIARC C3.3, WG2, 2006). Independent of the method one first has to identify the hazards. In quantitative risk analysis one has to consider as many scenarios as one can possibly think of; however, for emergency and disaster response one has to make a selection of a few representative scenarios to calibrate the organisation and to assess the local situation. For instance, there is only one response organization, which has to be prepared for all types of incidents anywhere and anytime. An additional—practical—reason for being selective is that a scenario analysis takes much more effort than a risk analysis, since the development process of a scenario over time requires more in depth knowledge of causes and consequences.

Most times, first a risk analysis is performed to get a general overview of the situation, and then a scenario analysis is performed to gain more detailed insight in the most important hazards and scenarios. Consequently, generally the results of a risk analysis are available at the start of a scenario analysis. However, hazard identification for risk analysis is not well developed yet, and does not provide a solid basis for the selection of scenarios in scenario analysis. The determination of the probability of causes and consequences is the weakest link. Probability of technical failure estimates are based on reliability data of technical equipment, which type of data has proven to be rather unreliable itself! The human factor further adds to the uncertainty, especially in the case of intentional acts (terrorist attack).[8]

[8]Although no likelihood can be estimated for intentional acts, relative probabilities shall be considered when considering various attack possibilities.

Hazard identification for risk analysis is partly a matter of science and technology, and partly a creative process. For routine matters, it may be sufficient to rely on empirical data and apply checklists or Failure Mode and Effect Analysis (FMEA). For novel or modified undertakings, more creative techniques are needed, such as *what-if* brainstorms and *Hazard and Operability* (HazOp) studies, for an overview of methods (see, e.g., Railtrack, 2000). Given a failure event, the cause-consequence chains leading up to it shall be unraveled (*fault tree*), subsequently one can 'branch out' the sequelevents in an *event tree*. The combination is called a *bow-tie*, Figure 7, extensively used in ARAMIS, a risk analysis methodology developed in the early years of this century as a European project (Salvi and Debray, 2006). It offers a rather standardized hazard identification for process installations. The branches of the event tree give clues of the time needed for a scenario to develop, such as the growth of a fire, the time to explosion of a liquid filled pressure vessel and the dispersion of a toxic.

The advantage of this method is the very systematic way it is set up. Disadvantages are—again—the lack of data and the amount of effort needed for the analysis. In Figure 7, a schematic example is given. The fault tree of possible cause consequence routes is related to the critical event, while the event tree branches out to effects by various types of fire, explosion, throw of debris and dispersion of toxics. Relative probability values may be attributed to the various branches.

Event trees for incident events in the process industry are relatively well developed, but for several other aspects of the build-up environment, such as aircraft crashes, large scale fires, terroristic attacks with explosives, and the like, no such ready-to-use *event trees* are available, but still need to be developed.

For the purposes of scenario analysis, it is not necessary to fully develop the *event tree* with corresponding event occurrence probabilities. Most importantly all damage mechanisms need to be identified (accidental or intentional; explosion, fire or toxic release; different sequels: heavy smoke, building collapse, large scale evacuation) and maximum realistic scenarios need to be defined in accordance to the chosen probability value for disaster control (see before Section 2.1). This implies another working method than is customary to risk analysis. For a risk analysis one starts by selecting an extent of loss of containment (LOC), e.g., a diameter of a hole in a pipe. These are clas-

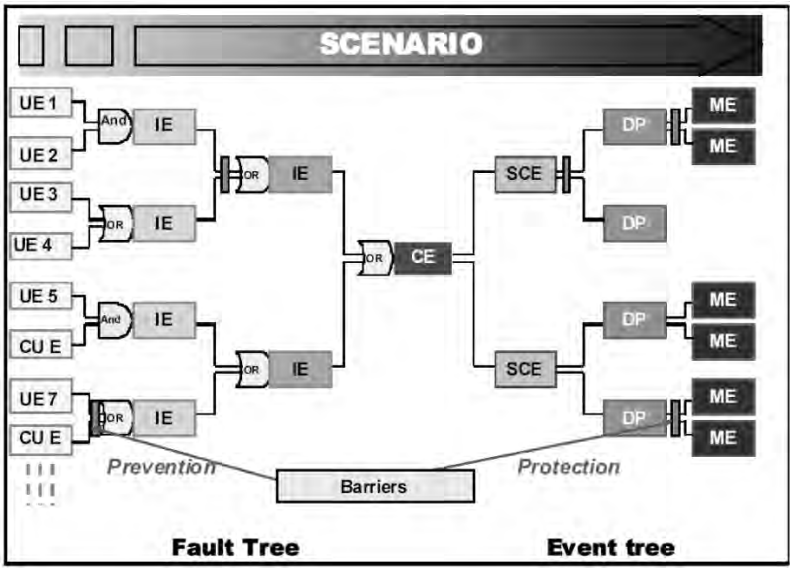

Figure 7. So called bow-tie diagram used in the ARAMIS project (Salvi and Debray, 2006), with left the fault tree with its AND and OR gates connecting to basic Unwanted Events, UE 1-7, in components some of which are conditional on a CUrrent "Event" operation—CU E, all causing Initiating Events—IEs, in subsystems leading up to a Critical Event—CE, in an equipment with loss of containment of a hazardous material. The last level of IE before the CE is also called the Direct Cause. On the right side, one notices an event tree with secondary critical events—SCEs. These follow the primary containment failure and can consist of formation of a liquid pool or a jet leading to so called Dangerous Phenomena—DPs. For a chemical complex, 13 types of DP are defined varying from a pool fire to a toxic cloud, and from explosion to missile ejection. A Major Event—ME, is defined as the significant potential effect on "targets". The latter are people, structures, or the environment and the effects thermal radiation, overpressure, debris impact and toxic load.

sified as, e.g., pin hole, large hole and full diameter failure. The next step is then to calculate a corresponding frequency of such a hole, e.g., 4.10^{-5}/year for a large hole. For scenario analysis, the sequence is the other way around: First, a probability level, e.g., 10^{-4} or 10^{-5} is chosen in accordance with the ambition level of the policy makers, and subsequently a hole size is estimated that corresponds with this frequency level. By lack of statistical data, expert opinion is indispensable. To this end, a data base of incidents and calamities needs to be developed, with probability values of incident occurrence, and nature and extent of

damage (event trees mentioned before). This is to a certain extent available for fires in buildings and accidents with hazardous materials, but usually with few details. For risk analysis this will be sufficient, but scenario analysis requires more detail in particular with respect to time, so the historical accidents have to be analyzed and described anew.

4.3. CONSEQUENCE ANALYSIS

4.3.1. *Methods and Models*

A consequence analysis is made up of a combination of an effect model and a damage model. Generally, static models are employed to describe the (physical) effects and the resulting (lethal) damage.[9] Damage encompasses people killed, but also people injured, materiel, economic, environmental and reputation damage. The weak link generally is the exposure pattern, because this requires assumptions about behavioural patterns and dynamic modelling in relation to the response options (escape/flight or shelter in place, rescue and medical assistance). Exposure is treated partly here, and partly in relation to the response models (in Section 4.4).

The effects (and hence also the damages) of most types of incidents cannot be sensibly modeled, due to the variability in outcomes such as with a knifing incident or a train collision. For this type of incidents the consequence analysis is limited to an educated guess about the maximum realistic amount of damage than can be expected. It goes without saying that the composition of the scenario analysis team is decisive for the acceptance of the estimated damages in such cases. Incidents with hazardous materials are forming a favorable exception. Physical effect models are available (release models, Yellow Book—PGS #2, 2003) and may be used in scenario analyses. However, the related damage models (Green Book—PGS#1, 2003) are restricted to direct mortality and are unsuitable for use in a scenario analysis. Instead damage models are needed that can be integrated with evacuation/flight-models and with emergency and disaster response models (see Section 4.4).

[9] Sometimes dynamic models are used, such as Computational Fluid Dynamics (CFD) models, but the results are generally used in a static manner and are not integrated with a damage model.

4.3.2. *Decision Criteria and Related Data*

The ambition level for 'controllable' incidents is to have no secondary lethality. This ambition has to be made SMART[10] to be usable in practice. Timely self-rescue and medical assistance have been put forth as the *measurement stick*s for the system of emergency and disaster response as a whole. The available parameters and data are described below. Also, the status of the criteria should be *a priori* clear. For example, in the Netherlands, the obligation to assess the local conditions for emergency and disaster response (see Section 1) is restricted to accounting for the efforts that were undertaken to reduce the risks, and is not extended to comply with the group risk criterion.

Generally, the following rule is used for assessing self-rescue: time available shall be larger than time needed. As decision criterion is proposed that the available time shall exceed the necessary time for all potential victims (irrespective of age, gender and impairments) with the calibrating scenarios. Self-rescue is obviously only relevant in dynamic situations, with either a premonition, such as for a BLEVE and a storm, or for a noninstantaneous development, such as a fire and a riot. To what extent are data available to underpin such assessments? To date only data are available for fire. The authors are involved in research to extend this hazardous materials more in general, including toxic clouds and explosions. For indoor fires, untenable conditions have been specified by the International Standards Organization (ISO TS13571), based on the work of David Purser (2000), and have been reviewed in the European project UPgrading of TUNnels.[11] These data have not been validated however, and are only representative for the end state: total incapacity to flee. A more dynamic model with more subtle damage parameters seems to be called for.

The authors are involved in research to investigate the additional value of Acute Emergency Guidance Levels[12] to gain additional insight in the early impairment of the (intrinsic) self-rescue potential of victims by atmospheric toxicants. They will further try to include heat radiation effects of fire and blast and debris effects of explosion. The results so far are promising and will be published elsewhere. It is

[10] SMART: Specific, Measurable, Acceptable, Relevant and Time framed.
[11] www.uptun.com, see WP2
[12] http://www.epa.gov/opptintr/aegl/

concluded that a more dynamic type of modeling is required within the range from early impairment of self-rescue up to total incapacity to flee (Figure 8). Practically speaking it is suggested to make several *runs* to compare the results with AEGL and with ISO-TS data and to interpret the differences in outcome (sensitivity analysis).

The internationally agreed rule for emergency and disaster response is that all victims with life threatening trauma need to be hospitalized within the internationally agreed professional time limits.[13] The database on the causation of life threatening trauma by industrial toxics is rather limited. Historical data of actual disasters are far too scarce to be generalized. Expert estimates seem to be the only realistic way to push forward. The authors are involved in research to use the Toxicological Incident Knowledge (TIK) bank of the Dutch Poison Control Centre[14] to assess the need for hospitalization. As stated, the results will be published elsewhere.

4.4. RESPONSE MODELS

Evacuation/flight models are available, but need to be improved. Emergency and disaster response models are not available, but may be developed in analogy to the evacuation/flight models. Evacuation models

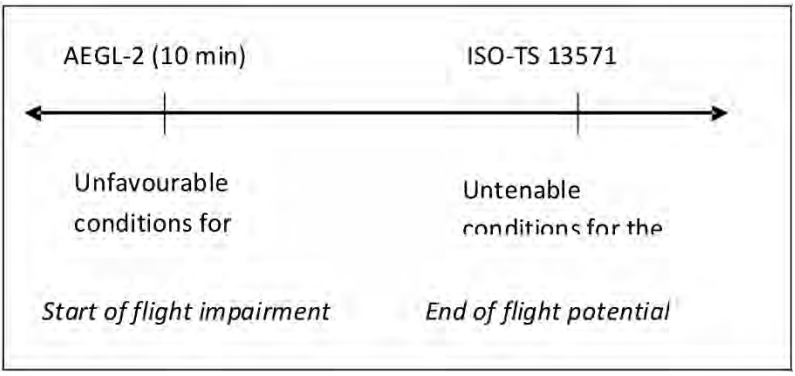

Figure 8. Relevant assessment criteria and available data for self-rescue.

[13] Victims with direct life threatening injury (triage class 1) within 1 hour and with indirect life threatening injury (triage class 2) within 4–6 hours. Time duration is measured form the moment of suffering the injury until the start of adequate treatment in hospital.

[14] In Dutch: www.vergiftigingen.info.

may be divided into building evacuation models and traffic models for area evacuation. Area evacuation models are developed mostly in relation to specific hazards with large premonition time, such as hurricanes and floods or nuclear accidents. Small area evacuation models for pedestrians in the ambient air are lacking to date. Over 30 building[15] evacuation models are available, each with its own way of treating phenomena such as: counter flow, manual exit block/obstacles, fire conditions affecting behavior, defining groups and disabled/slow occupant groups, delays/premovement times, elevator use, toxicity, impatience and drive variables, and route choice of the occupants/occupant distribution. For a review, see Kuligowski and Peacock (2005); Most models employ the equations given in: DiNenno *et al*. (2002): the *SFPE Handbook of Fire Protection Engineering*, NFPA, Quincy (MA), 3rd ed. There is no golden standard yet, so for the time being it is necessary to agree on the most suitable model to use and on the modeling assumptions.

4.5. SCENARIO SELECTION

The selection of scenarios for emergency and disaster response will probably never be completely fixated and standardized, but the degrees of freedom may be considerably restricted by defining the conditions for the calibrating scenarios in terms of relevance for (1) emergency and disaster response and (2) for the local situation and the system under consideration: If, in addition, the quality of the analysis process is assured by stipulating a number of process requirements (see further, Section 5), a consistent set of scenarios may result.

4.5.1. *Relevance of Scenarios for Emergency and Disaster Response*

Emergency and disaster response are consequently mentioned in unison in this article. In fact disaster response is a virtual organisation that is built on top of the regular structures for emergency response. Emergency responders, such as fire fighters and ambulance crews, do not only handle the daily routine emergencies, but also serve as first responders in large scale disasters. They do all the practical work, at least

[15] Some of the models have originally not been developed for buildings but for, e.g., cruise ships, or oil drilling platforms such as MUSTER and Building EXODUS.

during the first couple of hours after a disaster strikes! Consequently, they also have the most knowledge of scenarios that may realistically happen. Also the needs of emergency response have to be dealt first with, before one can turn to the needs for disaster response. Overall three types of scenarios may be distinguished, that are relevant for:

1. Emergency response on a daily routine basis
2. Disaster response to maximum realistic scenarios
3. Crisis response with involvement of vital infrastructure.

Every type of scenario has its proper decision criterion. For emergency response, the timeliness of the response is all-important, for disaster response in addition the capacity of the response is at stake, and for crisis response the vulnerability of the daily life is an issue.

The first priority—and the most basic requirement—is that regular emergency services arrive in time. This is not a given fact in our increasingly complex society. The emergency services have to conform to professional or political time limits,[16] but designers of urban environment and of structures generally do not have to take account of these limits.[17] A more strict interpretation of the time limits for emergency response is badly needed. If designers and emergency services would strictly adhere to the time limits for emergency response, this would constitute a major safety improvement. To be able to arrive in time, emergency responders need open approach routes, and fast and safe access routes to the scene. It is a challenge to see to it that proper conditions are met for, e.g., accidents on a highway, fire in a high-rise building or underground facility, a heart attack in a shopping centre or in a train, or an occupational accident in an industry park.

Besides a timely arrival at the scene, also sufficient capacity for disaster response is necessary. The capacity is not only dependent on the availability of responders, but also as mentioned before on

[16] In many nations emergency services have to conform to arrival time limits. These limits are adjusted to the local situation and vary widely. In a densely populated nation as the Dutch ambulances have a legal obligation to be with a patient within 15 minutes, but in sparsely inhabited areas of Australia, one struggles to be in place within a few hours.

[17] In Building Codes there may however be requirements for the access routes of the fire brigade.

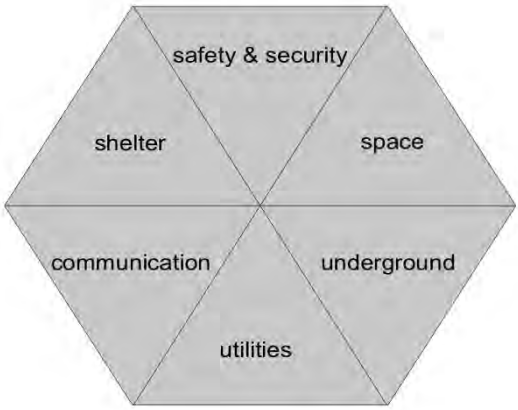

Figure 9. Characterizing terms for the conditions of first responder work.

the conditions for approach, access and working conditions for disaster response on the scene are shown in Figure 9 and are described here in some more detail.

1. Safety and security are obviously a first concern. If responders have to wear protective gear or take account of booby traps the access to the scene is cumbersome and time consuming.
2. The underground should be regular but not slippery to prevent secondary incidents and to be able to create a casualty nest where trauma victims can be laid on the floor or ground.
3. The availability of light and water may seem obvious, but remains problematic in many situations. The same holds for power supply in indoor situations. The use of fossil fuel powered generators in indoor environments, such as traffic tunnels, not only produces toxic fumes but also results in noise levels that preclude conversation.
4. Means for communication are vital for the coordination of the operation at site. In an escalator, or at a refinery (between large metal containers), this is generally not possible. Also, several tunnels lack *leaky feeders* to assure that GPS-signals are received.
5. The victims, either mobile or on a stretcher, need shelter from the weather conditions and some privacy. Immobile victims

may quickly develop hypothermia, which worsens their prospects considerably. Hypothermia is of special concern in, but is not limited to, moderate and cold climates.

The scenario selection is not complete, if one has not performed a last check on the involvement of vital infrastructures. Vital infrastructures may be interpreted strictly in the sense of national and higher interests, e.g., a route that is part of the trans European Network (TEN) for road and rail traffic and transport. Vitality may also be interpreted on the local level, in terms of the importance of this route for the local community. The vulnerability of societal functions cannot be well defined, since it concerns indirect consequences of the incident such as decrease of employment and damage to image and reputation. Local customs and local expertise dictate this final check.

4.5.2. *Relevance of Scenarios for the Local Situation*

The calibrating scenarios shall be representative for the incident situation, the locals circumstances and the response efforts. The size and tempo of the response operation provides clues to what shall be prioritised in a given case: control of the incident, self-rescue, or emergency and disaster response and of what kind? To this end a calibrating scenario is selected for every relevant damage mechanism separately. The calibrating scenarios should put the primary processes at the scene to the test. These consist of the incident process, the efforts to get the situation at the source under control, the self-rescue and the rescue of victims, as well as the medical assistance on the scene. Certain scenarios may in addition require special efforts to gain access to the scene, such as scenarios with explosions and building collapse, or storms and floods.

The procedure consists of three steps:

1. First it is necessary to identify all response processes that have to be put to the test, e.g., self-rescue, fire fighting, rescue and medical assistance.
2. Next, one may determine which damage mechanism is critical for which response process. For example, fire is often critical for the processes of self-rescue and fire fighting. Extrication situations are

generally critical for rescue teams. Panic in masses, or other disasters with an initial peak of trauma victims that can readily be picked up, are critical for the capacity of medical assistance. Of course, there are also situations imaginable that put high demands to all response processes at the same time. For example, after a blast it is difficult to reach the scene; at the scene secondary fires may have to be controlled and many trauma victims may be lying in the near field streets; other victims may be hard to reach because they are buried under rubble or locked up in damaged buildings; in the far field mobile victims with glass wounds may be present, hindering response operations at the site and flooding first aid departments in all nearby hospitals.

3. Finally, the probability criterion for disaster control is applied to determine the level of control needed for the individual response processes.

5. Scenario Analysis for the Build-Up Environment

5.1. USE OF SCENARIO ANALYSIS AT VARIOUS PLANNING STAGES

The urban 'tissue' is shaped by land use and infrastructural plans, and is further detailed by construction (and upgrading) plans for living quarters, industry and commerce, as well as for recreational facilities. All types of plans are of interest to emergency and disaster response services, be it in various ways:

Land use and infrastructural plans: Land use and the large scale infrastructures determine the conditions for self-rescue and emergency response Area evacuation may, e.g., be facilitated by radial routes. The arrival of responders may be promoted by, e.g., service lanes. Fire fighting may need back up capacity from water basins in the neighbourhood. Zoning, compartmentalisation, and barriers serve several purposes, such as limiting exposures, facilitating access for responders and creating stop lines for source control.

Licensing of activities involving hazardous materials: Licenses set limits to the quantity of hazardous materials and to the operating conditions and therewith to the magnitude of scenarios. For example the size

of a process vessel or a storage tank may be limited, the speed of vehicles may be restricted and crash barriers may be installed on roads.

Granting of building applications: Building licenses pose constructive demands and specify the layout and therewith determine its vulnerability to damage and the possibilities for self-rescue. In the planning stage the hull may, e.g., be reinforced against fire, explosive or toxic loads, and the capacity and length of exit routes may be improved. In existing buildings it may still be worthwhile to, e.g., install an alarm system, an extraction system for smoke and heat, sprinklers, or fire resistant glass, or make it possible to shut off the ventilation.

5.2. SAFETY CONSIDERATIONS IN VARIOUS STAGES OF DEVELOPMENT

The issues that have to be dealt with in scenario analyses vary with the stage of the planning process. In that respect six stages are distinguished:

1. Decision to develop a plan
2. The land use planning stage
3. The design stage
4. Construction stage
5. Exploitation stage
6. Renovation stage.

(Ad 1) *Decision to develop a plan*: Ideas and plans need some freedom to develop the plan before one starts with *ifs* and *buts* about inferred interests such as safety. The focus is in first instance mostly on economic gain and societal utility. Nevertheless, safety and security have to be considered in a marginal fashion even in this first phase, e.g., in a quick scan. The main issue in this stage is whether a sufficient level of safety/security can be realized within the financial and spatial boundary conditions and how various alternatives will perform. The emergency capability that can be mobilized already locally is an important factor. For example, the Rotterdam harbor area is in that respect different from the conceptualized ‘Energy valley’ in the sparsely populated extreme north of the Netherlands, in Delfzijl.

(Ad 2) *Land use planning*: Once it has been decided to realize a plan, it becomes important to choose a location or trajectory. This choice is among others influenced by safety considerations. Mostly strategic issues are at stake, such as the safety concept (e.g., the safe haven concept for subway stations) and the response operation strategy play (e.g., 'stay and play' or 'scoop and run'). Also restrictions may emerge from the building method (e.g., wood, concrete or steel) that have safety consequences (also during the building phase, e.g., drilling or cut and cover methods for tunnels). Comparative risk assessments may be performed to assess the possibilities for self-rescue and emergency response action.

(Ad 3) *Design*: In the planning stage usually a functional design has been developed. This will now be elaborated to a technical design and finally to a specification. A selection has to be made of dimensions, materials and technical installations as well as of organizational options about exploitation of the structure together with requirements dictated by a safety management system among which a calamity organization. This kind of choices may be supported by semiquantitative scenario analysis considering the layers of protection offered by the structure. Such analyses provide answers to questions about the number of victims that may rescue themselves in time and the number of trauma victims that may be helped in time.

(Ad 4) *Construction*: During this stage, the actual safety of construction workers and the safety of the public in the direct vicinity are important. Issues are among others child safety around the building pit, continuity of traffic, and access to the scene for emergency responders.

(Ad 5) *Exploitation*: Before the construction is taken in use, acceptance tests may have to be carried out. Scenario analyses may be helpful in this stage to obtain procedures for safe use such as calamity plans, training and practicing of alarm situations, maintenance and monitoring.

(Ad 6) *Renovation*: Renovation of some extent will give rise to the application of a revision license. This generates a good incentive to reexamine the safety situation and to take additional measures if necessary.

6. Conclusions

- A sketch is given of various aspects of planning emergency response to improve resilience of ever more complex urban area and its structures of high-rise buildings, traffic choke points, shopping centers and other public places making use of multiple use of space. Risk source can be terroristic act, a major traffic mishap or an incident with hazardous materials.
- First of all policy makers have to decide on an ambition level of protection and remaining risk and to draft a disaster plan. The remaining risk shall not only be in terms of people killed, but also people injured, materiel, economic and reputation damage. The remaining risk is to be included in the disaster plan and agreed.
- Whether this ambition level is achievable with existing emergency responder capacity shall be verified against calibrating scenarios. In case capacity fails additional protective measures in industry, structures/buildings or expansion of the capacity will be required if the risk generating source is maintained, e.g., for economic reasons.
- A guideline has to be developed to generate and select scenarios on the basis of existing results of Quantitative Risk Analysis in a given region (risk profile of the region). Various factors that play a role at the selection have been analyzed.
- Layers of protection analysis seems to be a suitable tool to extend to Emergency Response planning because its focus on selected scenarios and the team building by the various stakeholders. It will enable feedback to the owner of the site with the risk source and a balanced decision to improve on protective measures or to reinforce emergency response. It has to be further developed for that purpose though.
- Further recommendations are given for the performance of scenario analysis in the various stages of planning such as land use planning, licensing, and realizing of urban structures, what steps can be distinguished in the process and how it should be done.

- Various models and data are lacking for performing satisfactory scenario analysis. For example no ready-to-use event trees for build-up environment exist, which hampers efforts. Also more detailed effect models of hazardous materials (dispersion, fire, explosion) are required and particularly in view of medical first aid planning bitterly data are needed on nature and degree of injury expectedly be caused given effects.

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IS IT POSSIBLE TO USE CFD MODELING FOR EMERGENCY PREPAREDNESS AND RESPONSE?

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Abstract: This paper provides a comparison of the results obtained by the FLADIS field experiments and the results of CFD modeling by Fluent 6.2. FLADIS experiments were carried out by the Risø National Laboratory (Rediphem database). Experimental trials were done with pressure liquefied ammonia. Meteorological conditions and source strength were determined from experimental data and simulated using the CFD approach. The initial two-phase flow of the released ammonia was also included. The liquid phase was modeled as droplets using discrete particle modeling, i.e., Euler–Lagrangian approach for continuous and discrete phases. The second part of this task was devoted to the inclusion of obstacles. High obstacles which cannot be modeled with increasing surface roughness were included. From the results is obvious that such obstacles influence the gas dispersion radically.

Keywords: CFD modeling; gas dispersion; ammonia; turbulence; Schmidt number

1. Introduction

Potentially hazardous gases are very common in industrial and also in domestic use. The term ‘hazardous’ means gas toxicity to the public or environment or flammability of the gas. These gases are usually stored in highly

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pressurized vessels in liquefied state at ambient temperature. If an accident happens and the stored gas is suddenly depressurized the resulting jet will consist of a gaseous vapor phase and a liquid phase containing particle droplets mixed with air. Concentrations of the released gas are then predicted by various types of models and the values obtained are used in the hazard and risk assessment studies or by authorities (e.g., fire department) in the case of an accident.

The most used models are simplifications of the conservation equations for mass, momentum and energy. The models used in the mentioned area can be distinguished on basis of the density of the gas released into light gases (the density is equal to that of air) and heavy gases (the density is much higher than that of air). As an analytical solution for light gas dispersion, Gaussian models have been derived from the diffusion equation and from observations made by the experimental work, i.e., the concentration of released gas is following the Gaussian distribution (Lees, 1996). The dispersion coefficients have been derived from experiments (Barrat, 2001). Heavy gas dispersion has been modeled mainly by box models. In a simple box model the gas is assumed to be a pancake-shaped cloud with properties uniform in the crosswind and vertical directions. The model then contains relations which describe the growth of the radius and height of an instantaneous release, or the crosswind width and height of a continuous release, presented for example in Spicer and Havens (1989). These simplifications do not allow to model complex geometries, they are derived for a flat plane geometry with no obstacles or for a two-dimensional model with a simple obstacle.

Another possibility is the CFD approach, i.e., simultaneous of balance equations (1)–(4) of mass, momentum and energy (Bird *et al.*, 2002) given bellow solving. The results obtained by the CFD modeling are more accurate because the wind velocity is completely resolved in comparison to the simpler models where velocity is a single value or a function of height. This is clearer in an area with high obstacles. Using the CFD set of equations, any real hazardous situation including gas release in the presence of buildings can be modeled (Venetsanos *et al.*, 2003). Moreover, in the CFD model, the second phase can be included. The gaseous phase (air–toxic gas) is modeled by the mentioned balance equations, and the liquid phase (droplets generated by a sudden pressure drop of the superheated liquid) can be modeled by a multiphase approach. This means that the second

phase is modeled by the same equations as the first phase or the droplets are modeled as discrete particles (Crowe *et al.*, 1998).

The buildings, or obstacles, strongly influence the flow and thus also the dispersion of gases. Due to the wakes and cavities behind buildings the residence time of the toxic gas is higher, the turbulence is increased and the gas is spread faster in the crosswind direction.

Numerical simulations are very important for the verification of models with measured data. Delaunay (1996) has performed numerical simulations of tracer gas experiments carried out at Porte Maillot in Paris. Hanna *et al.* (2004) used FLACS software to simulate the MUST experiment, Venetsanos *et al.* (2003) worked on the modeling of the Stockholm hydrogen gas explosion. All these works have validated the application of the CFD approach as a useful tool for predicting gas dispersion in the vicinity of buildings.

In the present work the dispersion of the liquefied ammonia release was simulated by the CFD approach using the commercial software package Fluent 6.2. Ammonia was chosen because it is toxic and increasingly used in the industry. Ammonia is usually stored in pressurized vessels in the liquid phase. After its release, a two-phase flow occurs near the release point forming an ammonia cloud which is denser than the ambient air. The temperature and density gradually approach values of the ambient air and the cloud exhibits signs of a neutral or even a lighter type of gas dispersion.

The dispersion of ammonia was modeled using a full set of numerically solved conservation equations with additional equations for turbulence and a discrete particle model for liquid particle droplets. The mixture phase which is composed of air and ammonia vapor was modeled by the Eulerian approach. The liquid phase consisting of particle droplets with different diameters is modeled by the Lagrangian approach to the discrete phase.

Data obtained by mathematical simulation were compared to the experimental data from the FLADIS (Nielsen *et al.*, 1997) field experiment. In this field experiment, the release rates were approximately 0.5 $kg \cdot s^{-1}$ unlike the most well-known field experiment, Desert Tortoise Series (Goldwire *et al.*, 1985), with release rates about 100 $kg \cdot s^{-1}$, these are much higher than those presented in the FLADIS experiment. However, the smaller amounts of ammonia release occur more frequently in practical situations. Other differences are a lower ambient temperature and higher humidity, which are more representative for

the European climate, comparing to the Desert Tortoise Series. The FLADIS experiment was chosen also because of its perfectly organized data, and the free access to them on the webpage.

Furthermore, the buildings or obstacles were placed into a computational domain to see the influence of obstacles on the dispersion. In our work three different configurations of obstacles were chosen.

2. Governing Equations

The following Reynolds averaged Navier–Stokes (RANS) equations of mass, momentum, energy and species balances with mass S_m, enthalpy S_h, momentum S_{u_i} and species source S_m, were used in CFD modeling in all three directions x, y, and z (Fluent, 2005) as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = S_m \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho u_i\right) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\left(\mu + \mu_t\right)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i + S_{u_i} \tag{2}$$

$$\frac{\partial}{\partial t}\left(\rho c_p T\right) + \frac{\partial}{\partial x_j}\left[u_j\left(\rho c_p T\right)\right] = \frac{\partial}{\partial x_j}\left[\left(\lambda + \lambda_t\right)\left(\frac{\partial T}{\partial x_j}\right) - \sum_i h_i \vec{J}_i\right] + S_h \tag{3}$$

$$\frac{\partial}{\partial t}\left(\rho Y_n\right) + \frac{\partial}{\partial x_j}\left[u_j\left(\rho Y_n\right)\right] = \frac{\partial}{\partial x_j}\left[\rho\left(D_{n,m} + D_t\right)\frac{\partial Y_n}{\partial x_j}\right] + S_n \tag{4}$$

where $\mathrm{Pr_t}$ and $\mathrm{Sc_t}$ are turbulence characteristics of particular transport phenomena, i.e., heat transport and mass transport, respectively. The turbulent viscosity μ_t was calculated by the k–ε turbulence closure model defined as follows:

$$\mu_t = c_\mu \rho \frac{k^2}{\varepsilon} \tag{5}$$

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}\left[u_j(\rho k)\right]=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon \qquad (6)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}\left[u_j(\rho\varepsilon)\right]=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+c_{1\varepsilon}\frac{\varepsilon}{k}G_k-c_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad (7)$$

In Eqs. (5)–(7), the constants are: $c_{1\varepsilon}=1.44$, $c_{2\varepsilon}=1.92$, $\sigma_\varepsilon=1.3$, $\sigma_k=1.0$. The *k*–ε turbulence closure model was chosen because of its relative simplicity and already used by other authors, e.g., in the work of Sklavounos and Rigas (2004) who achieved a good agreement with experimental data through this model.

For the discrete phase, the equation of motion is defined as:

$$\frac{du_p}{dt}=F_D\left(u-u_p\right)+\vec{g}\frac{\left(\rho_p-\rho\right)}{\rho_p}+\vec{F} \qquad (8)$$

the enthalpy balance as:

$$m_p c_p\frac{dT_p}{dt}=\alpha A_p\left(T_\infty-T_p\right)+\frac{dm_p}{dt}h_{fg} \qquad (9)$$

where α, the convective heat transfer coefficient, is obtained from the Nusselt correlation reported in Ranz and Marshall (1952a, b):

$$\mathrm{Nu}=\frac{\alpha d_p}{\lambda}=2.0+0.6\,\mathrm{Re}_d^{1/2}\,\mathrm{Pr}^{1/3} \qquad (10)$$

and the mass balance is defined as:

$$N_n=k_c\left(C_{n,s}-C_{n,\infty}\right) \qquad (11)$$

where k_c, the mass transfer coefficient, is obtained from the Nusselt correlation (Ranz and Marshall, 1952a, b):

$$\mathrm{Nu}_c=\frac{k_c d_p}{D_{n,m}}=2.0+0.6\,\mathrm{Re}_d^{1/2}\,\mathrm{Sc}^{1/3} \qquad (12)$$

3. FLADIS Experiment

Field experiments with the dispersion of pressure liquefied ammonia were carried out in the Risø National Laboratory (Nielsen *et al*., 1997). The source was a flashing jet oriented in the horizontal downwind direction, with the strength of 0.25–0.6 $kg \cdot s^{-1}$ and duration in the range of 3–40 min. Due to the evaporation heat became the flash boiling ammonia jet much colder and therefore heavier than the surrounding air. The main focus was to study the dispersion in all its stages, i.e., heavy gas dispersion (measured gas concentration in a 20-m distance) and then, further downstream where the flow developed into a plume of neutral buoyancy, the passive gas dispersion (measured gas concentration in 70- and 235-m distance). The main characteristics of the trials used in this work are presented in Table 1.

The source was a 6.3-mm (4.0 mm for the trial Fladis16) diameter nozzle pointing horizontally in the ideal downwind *x*-direction with an elevation of 1.5 m.

TABLE 1. Main characteristics of the FLADIS trials used in the CFD model

trial	$\dot{m}$ /$kg \cdot s^{-1}$	f	w/$m \cdot s^{-1}$	L/m	u_{10}/$m \cdot s^{-1}$	stability
Fladis9	0.40	0.160	20	348	5.6	D
Fladis15	0.51	0.184	24	396.8	6.10	D
Fladis16	0.27	0.194	30	138	4.40	D
Fladis21	0.57	0.200	27	–52.6	4.08	C
Fladis23	0.43	0.184	20	–112.3	6.74	D
Fladis24	0.46	0.186	22	–76.9	5.03	C
Fladis25	0.46	0.186	22	–201.5	4.71	D

$\dot{m}$ —release rate; f—vapor fraction; w—release velocity; L—Monin–Obukhov length; and u_{10}—wind velocity.

4. Boundary Conditions

The boundary and meteorological conditions were identical to the FLADIS experiment. The area used in modeling was 280 × 200 × 100 m in *x, y,* and *z* directions, respectively. Each emission was treated as a plume, i.e., a continuous release.

The following boundaries for the continuous phase were set according to Figure 1 no slip boundary condition on the wall with standard wall function incorporated in Fluent 6.2 with the roughness length of 0.04 m and boundary layer depth of 0.2 m, i.e., the distance of the first point from the wall. A symmetry boundary condition was applied to *y* and *z* planes. The atmospheric stability class is represented by the inflow boundary condition for the velocity

$$u = u_{10}\left(z / z_{10}\right)^{n} \tag{13}$$

turbulent kinetic energy *k* and dissipation of turbulent kinetic energy ε (Han *et al.*, 2000). The power law velocity profile was used according to the stability class reported by Barrat (2001), i.e., $n = 0.15$ for the stability class D and $n = 0.10$ for the stability class C. On the outflow boundary, the Neumann boundary condition was applied.

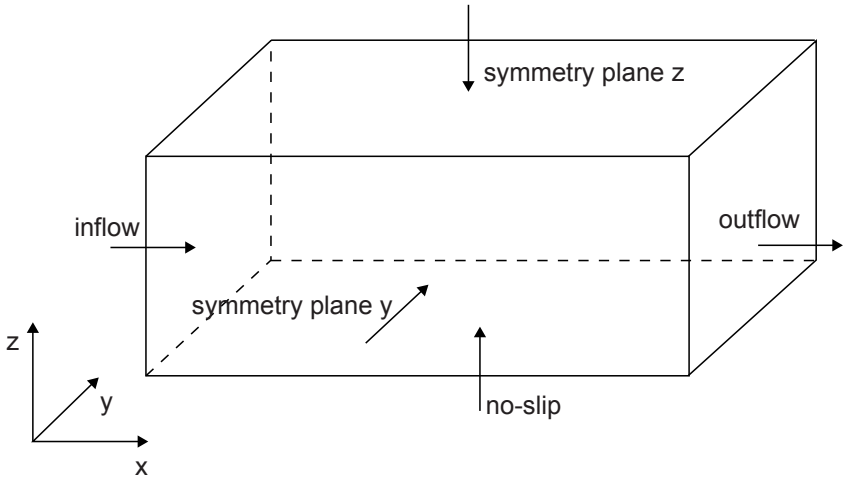

Figure 1. Boundary conditions: Length scales: *x* = 280 m, *y* = 200 m, and *z* = 100 m.

For the liquid phase, the initial temperature was also set to 239 K and initial speed to the value which corresponds with the velocity of the liquefied ammonia flow through the orifice. The source of ammonia release was modeled as a source in the balance equations, without exactly modeling the release from the pipe. Rosin–Rammler distribution for droplets diameter distribution of the ammonia liquid phase

was applied (Johnson and Woodward, 1999) as the mass fraction of droplets with diameter greater than diameter *d*:

$$Y_d = e^{-(d/\bar{d})^b} \tag{14}$$

with $d_{\min} = 10\ \mu\text{m}$, $d_{\max} = 100\ \mu\text{m}$, $\bar{d} = 50\ \mu\text{m}$, and $b = 2.5$. The initial amount of the liquid ml and vapor phase mv fractions was determined from the enthalpy balance:

$$f = \frac{m_v}{m_v + m_l} = \frac{c_p\left(T_0 - T_b\right)}{H_{vap}} \tag{15}$$

5. Solution

Fluent 6.2 was used for solving three-dimensional (3D) RANS. The discretization scheme was the first order upwind and SIMPLE pressure–velocity coupling (Patankar, 1980). Computational grids consisted of approximately 400,000 hexahedral volume elements. Steady state runs were terminated after ≈400 iterations allowing a reasonable convergence to be achieved. The convergence criterion was set to residuals equal or less than 10^{-4} for the continuity equation. The total time needed for the generation of steady states results was ≈45 min on a 2.8-GHz Intel® Pentium 4 Processor with 1 GB of RAM.

6. Results and Discussion

Unlike a wind tunnel simulation, the atmospheric wind direction and plume centerline position are not known a priori but have to be determined by observation. From the CFD modeling (steady state) point of view it may be more relevant to find a typical instantaneous plume profile than an average of a meandering plume. Therefore, it is necessary to determine the plume position from concentration measurements. This can be done using the fixed frame of reference where the local average concentration is calculated. Another alternative is to find an instantaneous position of the plume and then calculate the plume statistics, i.e., moving the frame of reference. Moving the frame of reference expresses the simulated results more accurately because it neglects

sudden changes of wind direction. The moving-frame analysis was used to process the experimental data. Experimental concentrations were obtained by interpolating experimental data with the assumption that the concentration profiles in the horizontal plane can be approximated by the Gaussian profile equation reported in Nielsen (1996), with longitudinal (*x*-direction) variation of centerline concentration $c_0(x)$, horizontal plume spreading $\sigma_y(x)$, lateral plume position $y_0(x)$, plume centre of gravity $\overline{z}(x)$.

$$c(x,y,z) = c_0(x) \cdot \exp\left\{-\frac{z}{\overline{z}(x)}\right\} \cdot \exp\left\{\frac{\left[y - y_0(x)\right]^2}{2\sigma_y^2(x)}\right\} \tag{16}$$

The statistical performance of the observed and predicted data is given in Table 2. The statistical performance measures (Chang and Hanna, 2004) are fractional bias (FB) with the ideal value equal to 0:

$$\mathrm{FB} = \frac{\left(\overline{C_0} - \overline{C_p}\right)}{0.5\left(\overline{C_0} + \overline{C_p}\right)} \tag{17}$$

geometric mean bias (MG) with the ideal value being 1:

$$\mathrm{MG} = \exp\left[\overline{\left(\ln C_0 - \ln C_p\right)}\right] \tag{18}$$

geometric mean variance (VG) with the ideal value equal to 1:

$$\mathrm{VG} = \exp\left[\overline{\left(\ln C_0 - \ln C_p\right)^2}\right] \tag{19}$$

mean relative square error (MRSE) with the ideal value being 0:

$$\mathrm{MRSE} = \left[\overline{4\left(\frac{C_0 - C_p}{C_0 + C_p}\right)^2}\right] \tag{20}$$

Normalized mean square error (NMSE) with the ideal value being 0:

$$\mathrm{NMSE} = \frac{\overline{\left(C_0 - C_p\right)^2}}{\overline{C_0}\,\overline{C_p}} \tag{21}$$

where C_0 is the observed quantity and C_p is the predicted (modeled) quantity.

TABLE 2. Comparison of observed and predicted data of the maximal concentration for trials (from TABLE 1) with statistical measures

	FB	MG	VG	MRSE	NMSE
	0	1	1	0	0
Heavy (20 m)	–0.035	0.933	1.039	0.028	0.023
Neutral (70 m)	–0.593	0.568	1.563	0.603	0.662
Far (235 m)	–0.910	0.456	3.523	1.898	2.393

A perfect model should have ideal values of statistical measures. Obviously, because of the influence of random atmospheric processes, there is no such thing as a perfect model in air quality modeling. Generally, it can be said that the heavy stage of dispersion is underestimated and the passive stage of dispersion is overestimated in the CFD model.

The results from the FLADIS experiments for the trials are presented in Figure 2 where experimental and predicted maximal (centerline) concentrations, C_0 and C_p, respectively, are depicted.

The results obtained from the numerical simulation of trial Fladis9 for the turbulent Schmidt number ranging from 0.1 to 1.3 are shown in Figure 3.

The influence of different Schmidt numbers was used because the generally used turbulent Schmidt number 0.7 is correct in the turbulent core. The turbulent Schmidt number is dependent on height within the boundary layer, as reported by Koeltzsch (2000). From this paper follows that the turbulent Schmidt number is not constant throughout the whole atmospheric boundary layer.

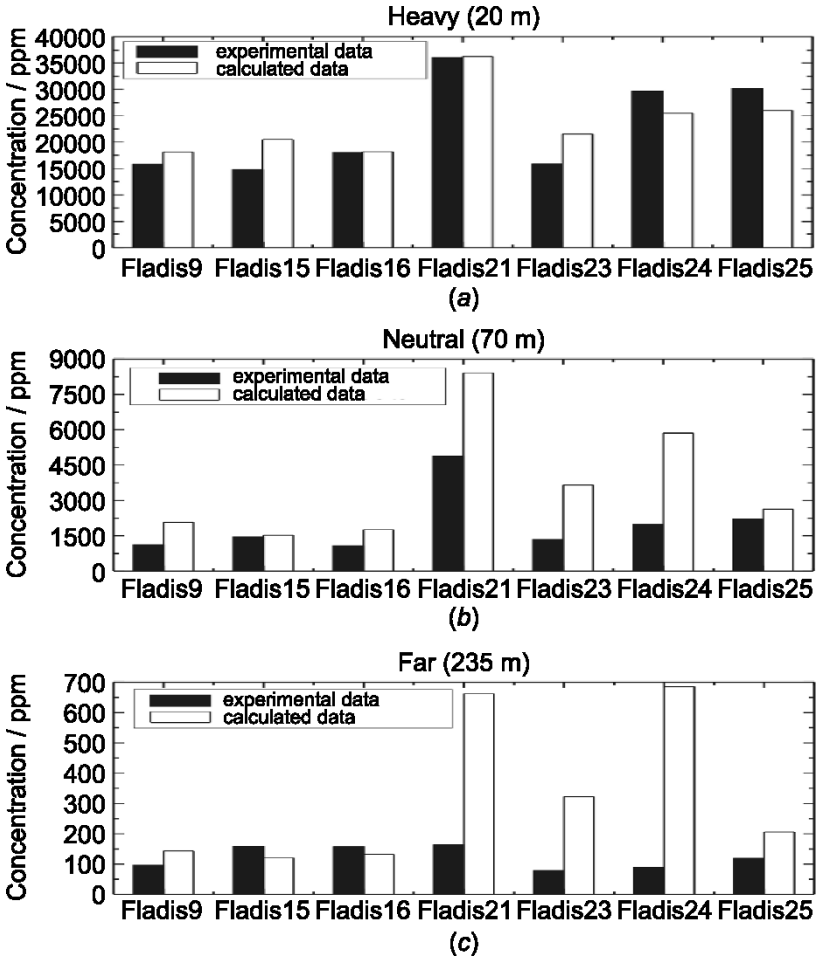

Figure 2. Centerline observed and predicted maximal concentrations for trials presented in TABLE 1, for three sensor arrays: (*a*) heavy (20 m), (*b*) neutral (70 m), and (*c*) far (235 m).

Another problem is that heavy gases tend to suppress turbulent mixing within a cloud bellow the ambient turbulent mixing. Thus the entrainment of ambient air into the cloud is neglected. This observation comes from the functional form of the dispersion coefficient given by the equation:

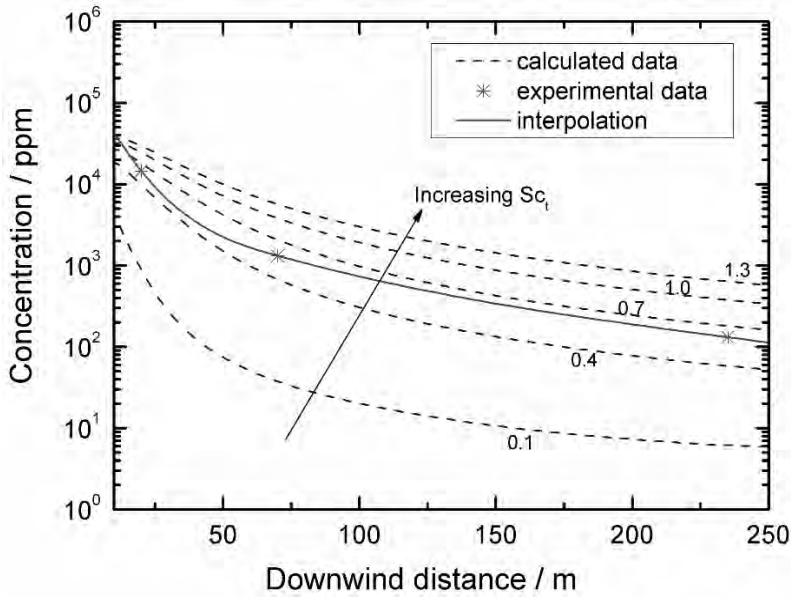

Figure 3. Influence of the Schmidt number for trial Fladis9 for the centerline concentration.

$$K = \frac{k u_* z}{\phi(\mathrm{Ri}_*)} \tag{22}$$

with the Monin–Obukhov profile function for negative buoyancy:

$$\phi = (1 + 0.8\mathrm{Ri}_*)^{0.5} \tag{23}$$

and the layer Richardson number

$$\mathrm{Ri}_* = \frac{g(\rho_c - \rho)H}{\rho_0 u_*^2} \tag{24}$$

Inspecting these equations the suppressing feature of heavy gases can be explained. If the Ri number is calculated for heavy gas, high values are expected, i.e., negative buoyancy. This value is used to calculate ϕ and then the dispersion coefficient. With the heavy gas cloud concentration increasing, the Ri number and also the ϕ function increase. Then, with the concentration of heavy gas increasing, will the dispersion coefficient decrease. In words of turbulence modeling;

the turbulent Schmidt number is increasing and the values of higher Schmidt number correlate well with the first phase of dispersion. The passive stage of dispersion is better correlated using asmaller turbulent Schmidt number; this corresponds with the Koeltzsch description of the turbulent Schmidt number being a function of height in the boundary layer.

From Figure 4, it follows that the computed concentrations for the turbulent Schmidt number 0.7 are narrower compared to those obtained experimentally. The maximal concentrations are computed relatively correctly. However, a closer look on Figure 4 reveals that the cross wind concentration profiles are not well correlated and this observation is also demonstrated in Figure 5 where the example of the numerical and experimental results of ammonia concentrations represented by isolines on the ground level for Trial 9 are depicted. From Figure 5 follows that the concentration isolines are more symmetric and less broad in the middle part than the experimental data in Figure 5.

This fact can be explained by fluctuations of the wind direction in a real atmosphere, which influence the calculation of average concentration values from the measured data. The simulated results are not dispersed so wide because fluctuations of the wind direction were not taken into consideration during the numerical simulations.

As reported, e.g., in Hanna *et al.* (2004) the k–ε model shows its weakness in a flat terrain with no obstacles where too much dissipation of turbulence was observed. The single realization of wind direction in steady state cannot take the fluctuation of wind direction and the turbulence production which is generated by these fluctuations into account. This would typically lead to an overprediction of the hazardous distance (overprediction of concentration). Building obstacles can ensure a sufficient production of turbulence.

Configurations with different types of obstacles were chosen to find out how the computed concentrations will be affected. Computational domain with different height, width, length and position of obstacles was examined (taking into account different dimensions of the obstacles ranging from 10–50 × 10–20 × 8–15 m for all three directions and the position of obstacles). It is complex and irregular as can be seen in Figure 6.

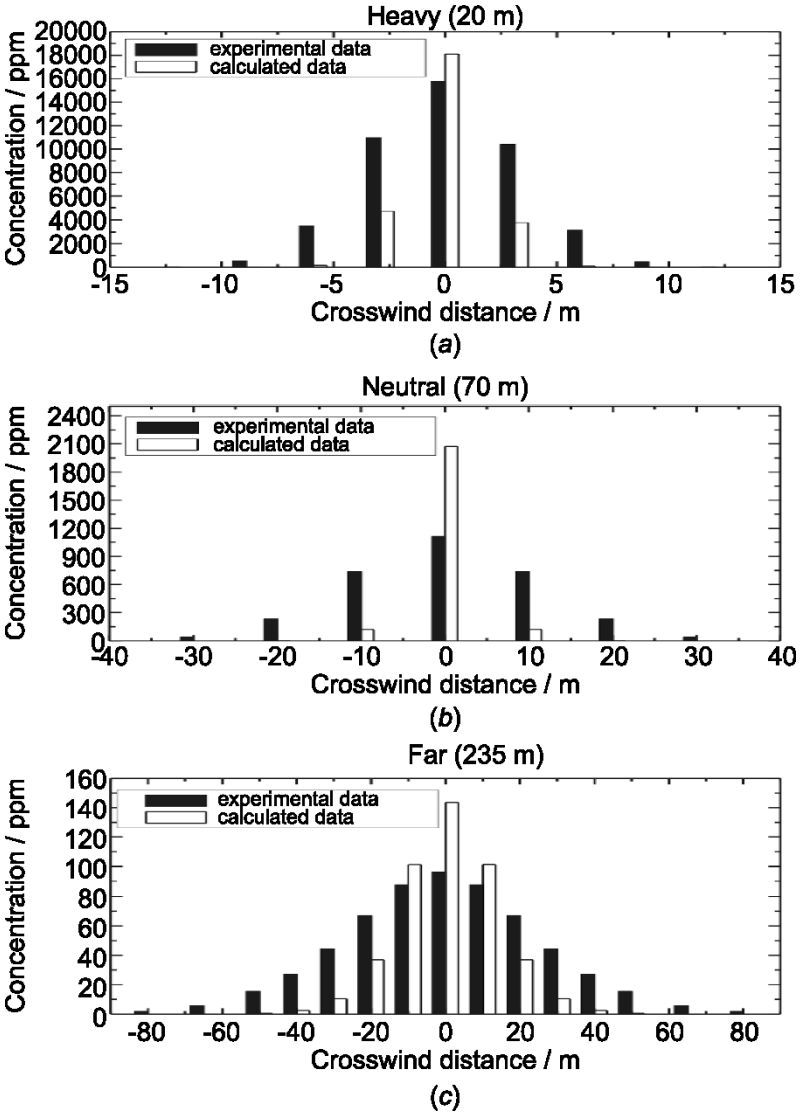

Figure 4. Crosswind observed and predicted concentrations for (*a*) heavy (20 m), (*b*) neutral (70 m), and (*c*) far (235 m) sensor arrays for trial Fladis9.

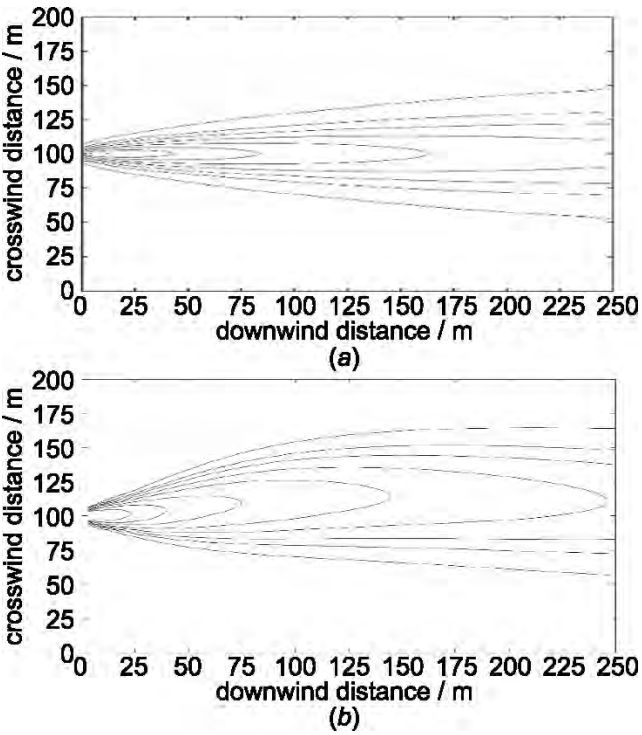

Figure 5. Computed (*a*) and measured (*b*) (interpolated) concentrations for trial Fladis9 with isolines 10,000, 3,000, 1,000, 300, 100, 30, 10, and 1 ppm.

From Figure 6 and Figure 7, it is evident that the calculated isolines are wider than without buildings. The turbulence (evoked by the presence of buildings and streamlines of wind blowing around the buildings) is influencing the concentration isolines. Thus, the width of the cloud is not dominantly sensitive to the turbulent Schmidt number. The width of the cloud is also a function of the geometry. As can be seen in Figure 6, the isolines are wider and more chaotic in comparison to isolines without obstacles (Figure 5). Furthermore, it is evident, that ammonia will disperse in the places which are not affected in the case without obstacles. The presence of obstacles has also an influence on the values of centerline concentrations.

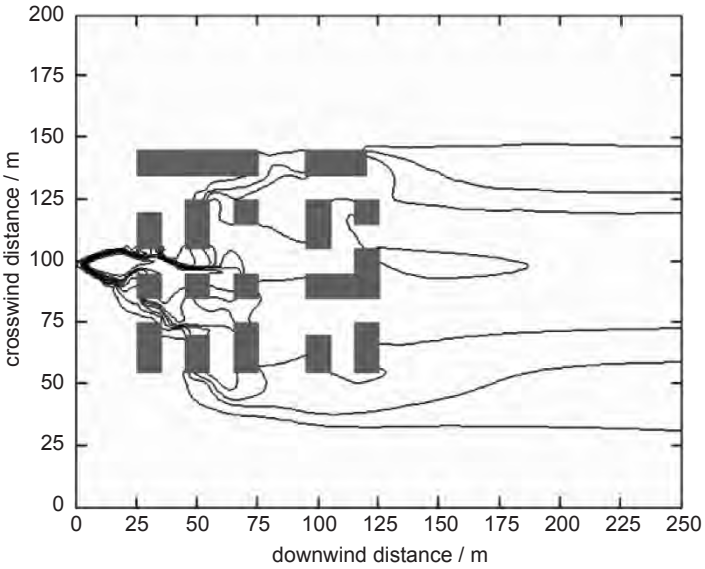

Figure 6. Computed concentration with isolines 10,000, 3,000, 1,000, 300, 100, 30, 10 and 1 ppm.

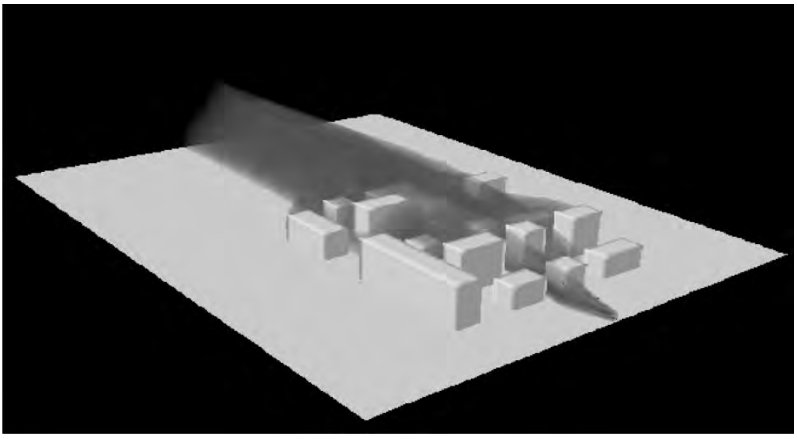

Figure 7. Three-dimensional realization for geometry with obstacles.

7. Conclusion and Recommendations

This work shows that CFD models can play an important role in prediction of toxic gases for emergency preparedness and response. The usually used models are approximated from the field experiments which are done in flat plane fields. Case studies based on the FLADIS experimental data were used to develop and evaluate CFD simulations of ammonia plume dispersion. But although are the CFD models able to model complex geometries, they are limited by the application of turbulence closure models. While atmospheric turbulence is known to be nonisotropic, this paper demonstrates that application of k–ε turbulence closure model appears to be sufficient for simulating plume dispersion. This simulation is even more successful if the turbulent Schmidt number is assumed not to be constant throughout the whole atmospheric boundary layer. On the other hand, simulation of plume dispersion with the presence of obstacles demonstrated that the concentration isolines are not sensitive to the change of the Schmidt number. However, in the future, CFD models after their validation against experimental data can replace experimental modeling in any known area of possible hazardous gas release.

RECOMMENDATIONS FOR CFD MODELLING OF DENSE GAS DISPERSION:

Two-dimensional calculation can initially be made to obtain far field vertical profiles of wind velocity and turbulence parameters to be used as inlet boundary conditions for the 3D domain. Velocity power profile or log profile can be used in the log profile including Monin–Obukhov stability functions. For the turbulent parameters, relations from Han *et al*. (2000) can be used.

The velocity values should match the experimental velocity at 10 m above surface. Symmetry boundary conditions or inflow boundary condition are used as boundary conditions of velocity at the lateral and top walls.

To avoid false outside transport due to finite size of the domain and possible discrepancies originating in the two-dimensional calculation, all inlet parameter horizontal gradients can be set to zero and the vertical velocity at the top of the boundary can also be set to zero.

Mathematical self-consistency between boundary conditions and internal 3D transport can be ensured by testing the corresponding flat terrain case to check for undesirable sources/sinks.

Concerning the two-phase flow nature of the release, the equilibrium thermodynamics simplification and the Raoult's law at phase change give reasonable results in terms of temperature and concentration predictions. The mixture mass, momentum and energy transport equations can be employed in estimating the flow and energy field. The heat transfer mechanism within the ground can be limited to conduction.

To define the size of the domain (excluding any disturbances) the following are recommended: upstream > 8*H*; downstream > 15*H*, and vertically > 6*H*.

In order to limit the CPU time, a nonuniform grid is preferred, with minimum grid size applied close to the ground, obstacles and source of the release. The grid can be expanded with an expansion ration no more than 1.2 as it draws far from these locations. The underground domain could be assumed to have the size of 1*H*, with 10 cells (vertically) of the same size. If a simple domain is modeled, structured mesh is a better choice. For both methods, adoption of the grid can be used to improve the results in areas with high gradients.

One or two equations turbulence modeling can be used to produce reasonable results. It is important that the selected model considers the local stability effects in a multiphase medium as well as the non-isotropic effects of eddy diffusivity.

Two approaches used for turbulent flow simulation in the complex environment are Reynolds Averaged Navier–Stokes (RANS) and large eddy simulations (LES). This work shows that RANS is applicable to steady-state or slowly evolving flows. It is valid for simulations involving longer time scales, and is more appropriate for continuous atomspheric release. On the other hand, for highly accurate simulations the LES approach, which resolves the most energetic eddies, is needed.

Acknowledgement

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9. Notation

c_p	specific heat capacity	$J \cdot kg^{-1} \cdot K^{-1}$
C	molar concentration	$mol \cdot m^{-3}$
D	Diameter of droplet particle	m
G_k	generation of turbulence kinetic energy	$kg \cdot m^{-1} \cdot s^{-3}$
H	Enthalpy	$J \cdot kg^{-1}$
h_{fg}	latent heat	$J \cdot g^{-1}$
P	Density	$kg \cdot m^{-3}$
J	species diffusion flux	$kg \cdot m^{-2} \cdot s^{-1}$
N	molar flux of vapor	$mol \cdot m^{-2} \cdot s^{-1}$
P	static pressure	Pa
Re	Reynolds number	
Y	species mass fraction	
Pr_t	Prandtl turbulent number	
Sc_t	Schmidt turbulent number	
Λ	thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$
M	Viscosity	Pa·s
Subscripts		
N	Species	
Op	Operating	
S	saturation	
∞	Ambient	
V	Vapor	
T	Turbulent	

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MEDICAL COUNTERMEASURES FOLLOWING TERRORISM CBRNE ATTACK IN URBAN ENVIRONMENT

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Abstract: This chapter explores various aspects of medical countermeasures—mainly, hospital-based, following a terrorism chemical, biological, radiological, and nuclear attack in urban environment. It points why the medical community does not seem to be ready to handle mass casualties following dispersal of weapons of mass destruction and attempts to provide certain guidelines that might help address the problem in the near future based on the international experience and the experience gained during the 2004 Athens Olympic Games.

Keywords: urban environment; chemical; biological; radiological; nuclear; CBRNE; terrorism; medical countermeasures; planning; weapons of mass destruction; WMD

1. Introduction

The threat of terrorism has been around us for a long time. In recent years, we have witnessed the release of the nerve agent sarin in Tokyo's subways, the bombings of the Alfred P. Murrah Federal Building in

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Oklahoma City (168 deaths, 5,500 emergency responders dispatched to the scene over 17 days, 600 injured), and the attacks on the World Trade Centre and Pentagon (over 3,000 deaths, nearly 2,400 injured), as well as other incidents affecting women's health clinics, social clubs and tourist resorts. The anthrax attacks of 2001 resulted in relevant few victims. However, despite 22 illnesses, including five deaths, both pubic health and medical care systems were required to dispend antibiotics to an estimated 32,000 individuals. On March 11, 2004, terrorist bombings on several trains in Madrid resulted in nearly 200 deaths and about 1,800 injured. Finally, the July 5, 2005 London bombings were a series of coordinated suicide terrorist blasts that hit London's public transport system during the morning rush hour resulting in 52 deaths and 700 injured.

The FBI defines terrorism as:

> The unlawful use of force against persons or property to intimidate or coerce a government, the civilian population, or any segment thereof, in the furtherance of political or social objectives.

Chemical, and to a greater extent biological, weapons of mass destruction (WMDs) are increasing in popularity in the terrorist community. They have the ability to inflict large numbers of casualties with a small amount of agent. Biological weapons are infinitely more attractive, mainly because the agents are considerably less expensive and can be developed by individuals with a minimum of training and little in the way of equipment. On the other hand, radiological dispersing devices named "dirty bombs" is the emerging threat of the 21st century; not used yet, but are easy to assembly and detonate are able to produce mass casualties' but mainly are able to isolate vast areas of inhabited areas in cities and critical infrastructures.

Health services planning for incidents of chemical and biological terrorism is needed to contain the exposure while treating the victims and to ensure that health and emergency services personnel do not become casualties in the process. Since the concern is less an issue of if than of when, preparedness is crucial. Planning for chemical and biological terrorist attacks encompasses many issues: the need for training of rescue and health care personnel; equipping rescue crews with the proper materials, and training them in the use of that material; formulating plans for the care of victims in health care institutions; and stockpiling needed medications and supplies; as well as specifying procedures

and facilities necessary for the identification of the agent and safeguarding any material which may be considered to be evidence in a criminal investigation.

Until recently, the medical community was required to deal with conventional terror. However, the dire circumstances of the last year have catapulted healthcare providers to anticipate other forms of mass destruction weapons—namely, chemical, biological, and radiation/nuclear (CBRN) terror assaults. We define a mass casualties' event as an incident in which the medical system is overwhelmed and the balance between resources and demands is undermined. Hence, the medical management of mass casualties' event presents a formidable challenge to the medical system. The principle aim of the overall medical management of the event is to decrease mortality and morbidity of the entire affected population, even at the cost of providing inferior treatment to the individual patient.

This paper will discuss common elements of the medical management of terror and provide guidelines for CBRN mass casualties' event medical organization and administration, while emphasizing characteristics of some unique forms of terror, based on the medical literature, the Greek 2004 Olympic Games' experience and the fact that:

> "Terrorists want a lot of people *watching* not a lot of people *dead*." (Jenkins, 1975)

2. Is the Medical World Prepared for a CBRN Terrorism Attack?

In a study *Research for a Secure Europe* (2002), conducted by the Eurobarometre, targeting what do European Union citizens fear, international terrorism, WMD proliferation, nuclear accident, and diseases rank amongst top ten. In a second U.S. study based on date from 30 hospital results revealed that these hospitals were not prepared to deal with CBRN events. Some interesting aspects from this study (Treat *et al*., 2001):

- 100% of sites were not fully prepared for biological incident
- 73% of sites were not prepared for chemical incident
- 73% of sites were not prepared for nuclear incident
- 73% would set up a "single room" decontamination process

- 13% had no decontamination process
- 3% (one hospital) had chemical antidote stockpile
- 0% had prepared media statements
- 25% had some training in WMD incidents
- 77% had facility security plan in place
- 50% were able to "lock down" the facility and
- 4% were aware of "secondary device" threat.

Why they were not prepared? Various explanations included need of unique equipment, specialized training, additional planning, extra money, lack of relevant information on the "CBRN subject," "it is not my job," fear of the unknown and the familiar attitude of "it cannot or will not happen here!"

Four years after the 9–11 incident that changed modern world, a 2005 study from the Trust for America's Health named "*Ready or Not? Protecting the Public Health from Disease, Disasters and Bio-terrorism*" revealed that only 3 States fulfilled all 8 criteria, 5 States fulfilled 7 criteria, and 13 States fulfilled 6 criteria. In the meanwhile, many organizations produced great many publications, guides, plans, handbooks, etc. trying to fill the gaps in medical CBRN defence. In 2006, the Trust for America's Health published the new version of the "*Ready or Not?*" study published: only 1 State (Oklahoma) fulfilled all 10 criteria of the survey. Some interesting key-points regarding U.S. hospital preparedness:

- 15 States had highest preparedness level to provide emergency vaccines, antidotes, and medical supplies from the Strategic National Stockpile
- 25 States would run out of hospital beds within 2 weeks of a moderate pandemic flu
- 40 States will face shortage of nurses
- Rates for vaccinating seniors for the seasonal flu decreased in 13 States
- 11 States and D.C. lack sufficient capabilities to test for biological threats—4 States do not test year-round for the flu, which is necessary to monitor for a pandemic; and

- 6 States cut their public health budgets from fiscal year 2005 to 2006; the median rate for State public health spending $31/person/year.

Another U.S. study on bioterrorism and mass casualties preparedness in United States hospitals revealed in 2005 that when personnel was examined by professional category, it was the residents those with the lowest training (less than 50%) on CBRN threats followed by physicians' assistants and nurse practitioners (little over 50%) (Nisk and Burt, 2005).

In 2006, a study published at *The Journal of Emergency Medicine* disclosed that from the front line health personnel (anaesthesiologists, emergency medicine physicians, general surgeons, and orthopaedics) of 34 hospitals, 47% were not aware of hospital's major incident plan, 23% of them had read the whole major incident plan, 30% focused only in their specialty's involvement in major incident plan while only 54% were certain about their role into the plan (Wong *et al.*, 2006).

In May 2007, at the World Congress on Disaster and Emergency Medicine, there was an interesting study on hospital preparedness for contaminated patients in Austria. In this study, 118 acute care hospitals were evaluated with the new hospital preparedness for contaminated patients (HPCP) score (Ziegler, 2007). The study concluded the following:

- Hospital must not rely on "on-site" decontamination
- Patients will surely bypass emergency medical service.
- Well documented risks for hospitals include: secondary contamination of staff and disruption of hospital services
- Hospital preparedness for contaminated patients is low
- Decontamination facilities and personal protection equipment were absent in many hospitals
- Contamination topic was included only in one third of the plans
- Ability to implement plans was doubtful
- Contamination related training and exercises? The exception, not the rule!
- Awareness of personal protective equipment in hospitals is particularly low.

Finally, the preliminary results of the EU funded ETHREAT study (European Training for Health Professionals on Rapid Response for Health Threats) are quite disappointed as well. Five hundred thirty one front line health professionals (FLHP) from 22 countries participated along with 93 CBRN experts from 16 countries. Approximately 50% of the FLHPs reported awareness of a National CBRN Plan, 67% were aware of a person of contact in case of a deliberate incident, 68% had last CBRN training in less than 24 months or never, 28.5% expressed high confidence in their personal protective equipment, and almost 40% had access to personal protective equipment in workplace. Knowledge regarding discrimination of natural vs. man-made incident was below average (chemical: 31.6%; biological: 303%; radiological: 27.3%) and so was preparation for mass casualties' management (chemical: 37.2%; biological: 46.8%; radiological: 28.6%). Level of knowledge regarding biological threats (57.6–64%) was by far better when compared to chemical agents (34.7–42.9%), perhaps, because biological agents comply with everyday medical work. On the other hand, the idea CBRN experts have about the FLHPs training is alerting since they rate it very low (8–20.7%).

All the above and many more relevant studies reveal that despite the level of terrorism threat, medical preparedness is not equally high although many things have been done during the last 6 years.

3. Why Medical Community is Reluctant to Contribute to CBRN Preparedness?

Medical people comprise a very complicated community entrusted with great responsibilities and duties. The combination of a very loose attitude towards the threat ("it will not happen to us") along with the fact that medical CBRN countermeasures are in fact a whole new medical specialty, make medical community reluctant to contribute to CBRN preparedness to the level they should. The first part of their argument collapsed during the Tokyo sarin incident in March 20, 1995. Medical and nursing personnel of the St. Lukes' International Hospital and Health Network deal with more than 650 casualties in the context of less than 2 h at the outpatient clinics of the hospital because this hospital happened to be the closest hospital to the Kasumigaseki subway station, one of the major attack sites. The second part reflects reality and it is true that CBRN training is laborious both physically and mentally and it

is like studying for a second medical specialty. Physicians and nurses need to learn from scratch all usual medical procedures while wearing inconvenient personal protective equipment and working under dangerous and highly stressful conditions. Continuing medical education is mandatory and for life and if there is no motivation, there is no way to attract qualified personnel no matter what the threat level is or will be in the future.

In case of a real incident, the most experienced medical person is performing triage in the field while the most experienced surgeon is performing triage in the cold zone. Both persons should be fit to do it and this means that a dedicated CBRN reaction unit should be in place in every hospital in order to deal with casualties of such severity and peculiarity. You cannot ask from the nontrained physician on duty to put his personal protection equipment and go down the parking lot to perform his duties. He will not last more that a few minutes before collapse! Some specialties would be certainly more busy than others, i.e., ophthalmologists, chest physicians, dermatologists, burn unit personnel, intensive care unit personnel, and psychiatrists/psychologists, but in real life, all medical people will become experts and will be involved because almost all organs and systems are involved in case of a chemical, biological, or radiological incident.

Although may look irrelevant, a note should be made for the security personnel of the hospital—if available. Security personnel should be trained in personal protective equipment in order to be able to handle crowd while preserving the integrity of their gas mask and filter. If security personnel cannot control the main gate or entrance of the medical facility, then the game is over; contaminated victims will flood the hospital and finally overwhelm the medical system.

4. What is the Real Picture of a CBRN Terrorism Incident?

4.1. CHEMICAL INCIDENT

A chemical incident usually will be accompanied by an explosion most probable during rush hour (i.e., early in the morning when people are escorting children to school or late in the afternoon when working people are going back home) in a highly populated area like city's downtown. Following the explosion and consequent release of chemical

agent, approximately 20% of those involved will remain on site because they are either dead or severely injured or contaminated. The remaining 80% will flee to every possible direction using all available means in order to save themselves, especially if they witness people suffocating from the chemical plume freed in the environment. These people will whelm all medical facilities seeking for help regardless they are truly contaminated or think they are contaminated ("*worried-well*"). The ratio between contaminated and worried-well is approximately 1:5 and this is the main cause of overwhelming of the medical system even of very advanced societies. State response resources will face heavy traffic problems that will surely delay their arrival at the incident site long enough to be able to provide essential life saving first aids and assistance. Of course, evidence collection and identification of the substance released is of crucial importance for practical, medical, and political reasons. For those needing assistance, there are three medical interventions that can be done on site: control of bleeding (due to mixed lesions: chemical plus blast injuries) with modern technology, i.e., haemostatic dusts like Quiklot™, respiratory assistance (all the way to intubation provided special equipment is available), and administration of antidotes (e.g., atropine, pralidoxime, diazepam). Rapid evacuation of casualties is critical.

From the above, it is clear that the state defence is almost automatically translocated to the hospital where all casualties will seek shelter. Therefore, hospital defence is very important in order to be able to control contamination and provide assistance to those in need.

If the incident site is far away from the hospital, there is enough time to organize basic reception of casualties and countermeasures provided that the hospital has a dedicated CBRN response team or unit. If the incident is close to the hospital, i.e., in a subway station adjacent to the hospital's premises, then the reaction is limited if any. Finally, we must not forget that hospitals themselves can become targets (asymmetric threats). In that case, there is no reaction time at all and improvisation is the only solution left and available. If the hospital has secure perimeter (fence), then crowd control is rather possible in combination with the existence of enough security personnel. If there is no secure perimeter, then there is big chance that contaminated citizens will be inside the hospital before anyone tries to stop them or secure the entrances of the building (Figure 1).

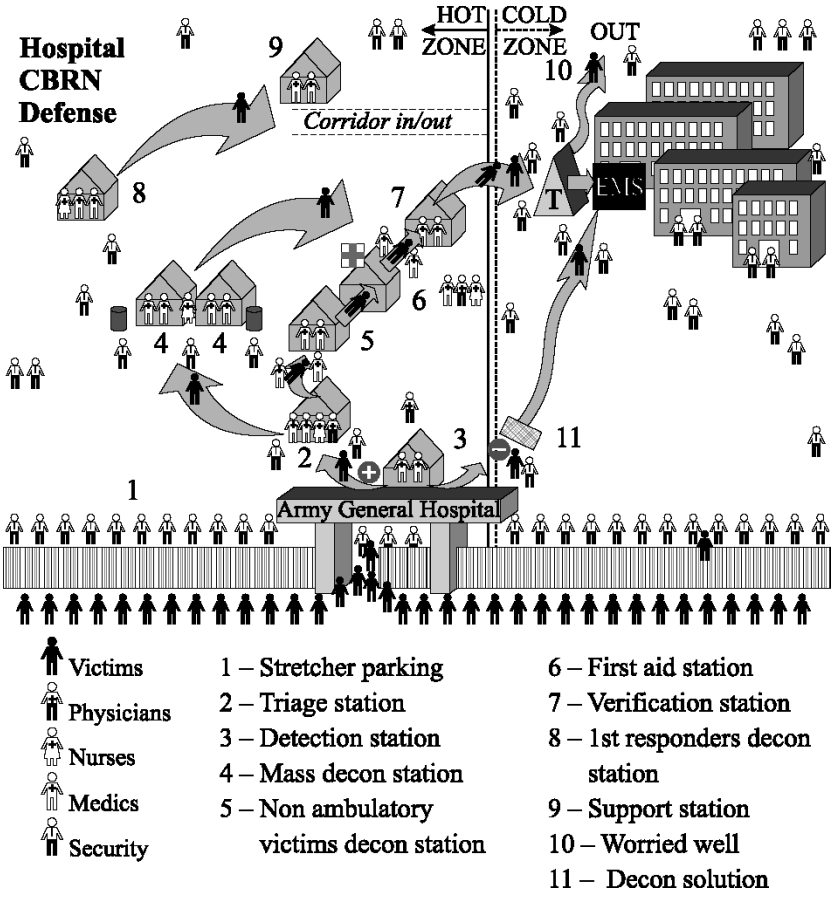

Figure 1. Chemical-radiological hospital-based defence.

Decontamination of casualties can be done on site—but victims cannot wait until special forces (first responders) to arrive, en route—inside the ambulances on the way to the hospitals (recommended by Israeli CBRN planners) or outside the hospital, usually at the parking lot. Special considerations should be taken if unfavourable weather conditions exist during the incident, i.e., low temperatures—risk for hypothermia. There are certain rules regarding decontamination; the most important are:

- Start decontamination as soon as possible
- Use immediately available resources

- Shower as many victims as possible
- Water is an excellent decontamination solution
- Do not delay to add soap or bleach
- Establish an emergency decontamination corridor (with fire engines)
- Employ “strip-flush” or “flush-strip-flush” method
- Disrobing is a method of (dry) decontamination
- Special considerations during decontamination (e.g., contact lenses, hearing aids, etc.)
- Wash (gently) 1–3 min per victim (depending on number)
- Keep families together
- Record victims if possible
- Consider privacy (mass media, religious considerations)
- Consider adverse weather conditions
- Consider language/religious problems and inhibitions
- Expect a 1:5 ratio of “contaminated” vs. “worried-well” victims
- Keep patients in safe area for observation (if applicable).

First Responders have always their own decontamination line.

When chemical casualties are decontaminated and clean, then handling is as usual with no secondary effects for the hospital personnel. Therefore, the most important of all is to keep contaminated victims in the outside of the hospitals and medical facilities.

4.2. RADIOLOGICAL INCIDENT

“Dirty bombs” (combination of a radioactive source like Cs-137 with explosives like TNT or C4) represent the new threat and although there is no active history yet, a detonation of such an improvised device is expected to cause tremendous problems not due to the number of casualties caused but mainly because of the radioactive contamination of vast areas and properties with huge social and economic impact. Similar principles as in chemical attack apply for a radiological incident as well. The only difference has to do with the invisible

nature of ionizing radiation and the little knowledge people have about it. People usually are unaware of the fact that approximately 82% of radiation comes from natural sources (cosmic, radon, internal, terrestrial) and that different types of radiation have different penetration power ($\alpha < \beta < \gamma$, $X <$ neutrons). In a contaminated environment, both casualties and personnel must stay as less as possible because health effects are proportional to doses exposed. In general, with doses up to 100 rad, there is no symptomatology present. When doses are in the sublethal (200 to 800 rad) or lethal (600 to > 3,000 rad) range, then fatality rates are high, sometimes reaching 100%. If trauma is present, medical responders must treat the casualty first and decontaminate later. If external radioactive contaminants are present, then decontamination becomes first priority and treatment follows afterwards. If radioiodine is present in the environment (e.g., following a nuclear reactor accident), then potassium iodine (e.g., Lugol's solution) should be administered within the first 24 h (otherwise, it will be ineffective).

Hospitals should be prepared to accept radio-contaminated casualties by following certain protocols (e.g., from the International Atomic Energy Association), addressing items such as preparation of emergency care department, personal protective equipment for the emergency personnel, accommodation facilities, waste management, etc.

4.3. BIOLOGICAL INCIDENT

Release of a biological agent could be overt or covert. In either case, there are certain indicators (syndromic surveillance) that can alert authorities about the possibility of a bioattack (i.e., people coming from the same area, with similar symptoms, out of season, sick animals in the same areas, etc.) but usually, when state realizes that hospitals are having more work than usual, it is too late. Depending on the incubation time of the microorganism released, there will be little if any time before the overwhelming of the medical facilities with sick people. The main problem with biological agents is that almost all of them at the initial stages look like flu-like illnesses and it takes special training in order to be able to identify that it is flu not anthrax. The good thing is that most of the agents respond well to available antibiotics (e.g., ciprofloxacin, doxycycline) provided they are given well before the official diagnosis—afterwards, it is usually ineffective.

Biological agents have the advantage that a very small quantity can cause many casualties compared to other agents (e.g., the LD_{50} for population within 1 km^2 is: 21 t of phosgene, or 4 t of nerve agent mustard gas, or 2 t of nerve agent tabun, or 500 kg of nerve agent sarin, or 5 g of anthrax spores (8,000–50,000 spores) depending on the environmental conditions, dispersal mode, diameter of particles released, etc. (Franz *et al*., 1997).

5. Medical CBRN Preparedness for the Athens 2004 Olympic Games

The Olympic Games is an international multisport event subdivided into summer and winter sporting events. Summer 2004 Olympic Games in Athens, Greece, was the first Olympiad post 9–11 and it was obvious that the whole world had been focused in the event for obvious reasons. Greece was the second smallest country to host the games and approximately 2 million visitors and billions of TV spectators worldwide were expected to watch the games. Greece was about to host 202 countries, 10,500 athletes and escorts, 4,000 Para-Olympic athletes, 6,700 technical officials, 5,800 dignitaries and International Olympic Committee members, 21,600 journalists, and 35,000 sponsors in 37 events, in 28 sports in 35 venues, in 5 different Olympic cities (clustering more than half the population of the country). Since CBRN threat was new, a new CBRN master plan should be established from scratch and that was a difficult thing to do, mainly, because more than 75 ministries, entities, and bodies should be gathered around the table, cooperate, synchronize, and effectively deploy in order to deal with possible asymmetric threats during the games. The CBRN incident management unfolded in four levels (political, strategic, operational, and tactical) with distinct groups for crisis and consequences management. Greece employed approximately 2,300 people for CBRN needs both operational and medical. One of the biggest problems to overcome was the integration and interoperability of civilian and military sanitary systems. Some of the lessons identified regarding medical CBRN preparedness for the 2004 Olympic Games are:

- Lack of integration between civilian and military medical and operational/response systems
- Lack of cooperation between national and international medical and operational/response systems
- Reluctance of civilian medical personnel to interfere with CBRN defense
- Reluctance to realize the need for continuous personal protective equipment training
- Different attitude regarding the magnitude of threat
- Denial of the possible death roll following a CBRN attack
- Disbelief regarding the national consequences following a terrorist attack
- Civilian-military medical cooperation and integration is mandatory.

Preparing for the 2004 Olympic Games revealed that medical CBRN defense is, in fact, a new medical/nursing specialty and as such should be taught at universities and medical/nursing schools. It is very important for (especially) young doctors and nurses to have some idea about the new threats and the ways to identify and handle them. Also, knowledge of operational aspects is important. Medical personnel must be aware of the working conditions of the people they are about to support and/or treat. Continuing medical education is mandatory and so is top physical/mental condition. Those in charge must have "personal" training and relevant experience. Personnel are performing in their extreme/top limits and many hidden psychological peculiarities (e.g., claustrophobic reactions) may arise. Team work is needed for the system to work effectively.

Following a hard preparation period, it was a great relief to run very successful Olympic Games and overwhelming with congratulation comments from states, organizations, and mass media worldwide.

6. Recommendations for the Future

It is generally accepted that CBRN operations last a limited period ("golden hour"); medical CBRN consequences last for decades. Chemical casualties from the Iran–Iraq war of the 1980s still visiting dedicated outpatient clinics daily at the Baqiatallah Military Hospital

in Tehran, is a vivid proof of this. Therefore, medical and nursing personnel must be prepared in advance, be well organized, be sufficiently equipped, and be trained both theoretically and practically in order to efficiently manage CBRN mass casualties. Hospitals represent the last frontier of the population regarding medical CBRN defence and need to be adequately prepared. Medical CBRN defence should be taught in medical schools.

On the other hand, we may, perhaps, review our current tactics and plans and adjust them for CBRN operations in urban environment. It is of significant interest the fact that planners adopt military mode of action and use it into urban environments. For example: in case of a terrorist chemical attack, first responders deploy upwind and set their equipment, decontamination stations, etc. as if they were at the battlefield with the enemy in front of them. Urban environment has certain peculiarities such as: people escape to more than one direction, "urban canyons" (spaces between high buildings) produce additional unique parameters that play significant role in the movement of the contaminated plume while traffic jams hinder prompt arrival of first responders at the incidence site and many more. A more realistic "urban" approach is necessary. Finally, new construction products will help minimize number and type of casualties (building stability, construction materials, window glasses durability) and contamination of properties (concrete absorption).

7. Summary and Conclusion

Terror is becoming an increasingly real threat to society each day. The different modes of terror comprise a new field of epidemiology that demands ongoing activities at all levels of prevention. Continuous preparations and readiness on behalf of all components of the medical society (administrators, EMS rescue teams, community medical staff, personnel of community, regional and tertiary hospitals, and rehabilitation centres) will enhance the strength and durability of society against conventional and CBRN/WMD terror attacks.

This chapter has shown that state must focus its medical CBRN defence at the hospital level since all victims will overwhelm medical facilities in case of a real terrorism attack with radio-bio-chemical weapons. On the other hand, medical community should reconsider its

role in the management of the new and emerging threats and participate more actively and effectively in preparedness and planning.

Following the unsuccessful IRA terrorism attack against former Prime Minister Margaret Thatcher, a member of the organization commended:

> They have to be lucky all the time. We have to be lucky only once!

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LAWS OF MOTION OF PEDESTRIAN FLOW—BASICS FOR EVACUATION MODELING AND MANAGEMENT

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Abstract: Despite numerous measures stipulated in modern buildings for people's protection in emergency situations, evacuation remains the process necessary for provision of safety. During evacuation, people organize flows and without knowing the principles of movement of such flow, it is impossible either to modulate this process, or to regulate the necessary sizes of evacuation routes and exits, or to estimate the risk of people's life and health damage in various protection systems. However, systematic studying principles of people's movement in flows began only in the second third of the last century. Therefore, we are practically witnessing these researches to come over traditional stages of scientific knowledge development: from empirics to formation of first generalizations and theoretical construction, and through them to theory. Today, it is necessary to summarize or, at least, present a brief study of such collective research and to disseminate their results for a wide use in order to increase the level of people's safety.

Keywords: evacuation; pedestrian flows; modeling; parameters of pedestrian flow; building design

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1. Introduction

The first scientific investigations (as they are the first to establish the main parameters of flows—density D, person/m^2, and velocity V, m/min, and to search for a connection between them) were carried out (Kimura and Ihara, 1937; Belyaev, 1938) in the ’30s of the twentieth century. However, it took long before these results were introduced into practice. The reasons for this are not only the conservativeness of designers or regulatory organizations, but the small number of the original empiric basis or the nonavailability of knowledge of many aspects of this process, for example, kinematics of the flow movement through the boundaries of neighboring parts of the evacuation path-way, without which it is impossible to modulate (calculate) flows as a continuous process. The establishment of the principles of kinematics was mainly prevented by a not really adequate model of flow structure, which corresponded more to the description of a marching infantry force.

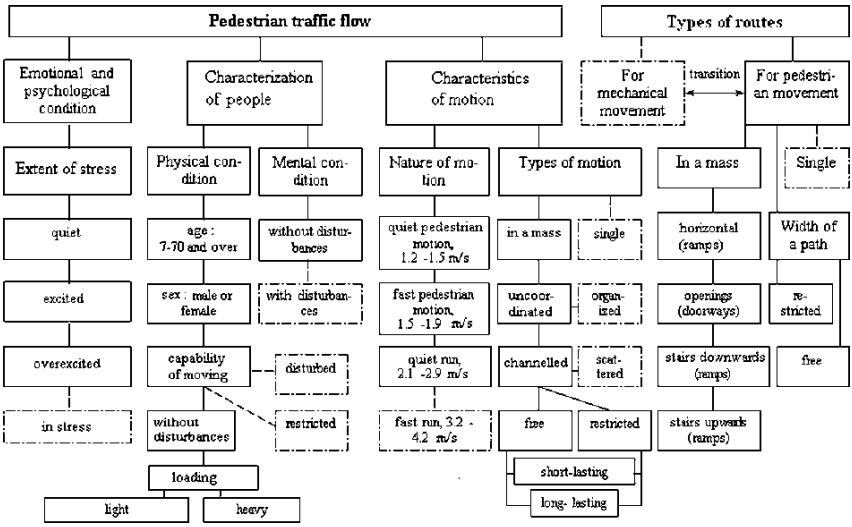
It may seem surprising but such view on the flow of people has been widely found today even in the construction companies, joint with famous foreign ones, designing high-rise buildings in the city of Moscow and in the materials of tenders presented by foreign companies for the reconstruction of the unique buildings of the Russian national heritage. The methods used by these companies for the purpose of sizing ways of evacuation and exits, clearly reveal the archaism of corresponding norms in their countries and the nonavailability of contemporary data concerning the research of flows by specialists who have developed these norms.

The discrepancy found between modern possibilities of computer modeling and outdated knowledge about people’s movement in flows, used even in regulation, obliges us to share such data and concepts in this respect which are widely used in our country.

2. Pedestrian Flow and Route Types

Pedestrian flow is a mass of people which is moving simultaneously and indirectly along a mutual route. This easy and traditional definition, however, needs to be clarified, because of the broad sense of different terms in it, which leads sometimes to incorrect understanding of the real process of “pedestrian flows.” Different types of movement, the

content of the mass of people, their psychological and physical state, different types of routes, etc. create the zone of correct implementation of the above-mentioned terms (indicated by solid lines in Figure 1).



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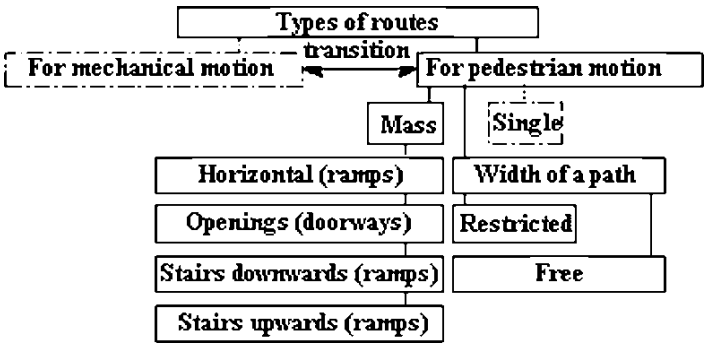


(*b*)

Figure 1. Overview diagram of various ‘parameters’ playing a role in pedestrian traffic flow (*a*) and evacuation routes (*b*).

3. Methodology for Actual Observations and Experiments

Actual observations and experiments remain. The main way to obtain basic data about qualitative and quantitative characteristics of pedestrian flows, about their phenomenology, etc. remains. These are also valid in checking theoretical assumptions and hypotheses. An experiment is based on aimed control of different characteristics of pedestrian flow or of a route of its movement in order to learn about the process from the degree of influence of different factors. Such control is impossible in actual life, because in reality, the experiment is conducted by Nature itself, and the rules of this experiment frequently are not known to an observer. The methods of gaining initial data are common for either actual observations or experiments, i.e., visual method; film-and-camera method (movie or photo method); video-recording method (Figure 2).

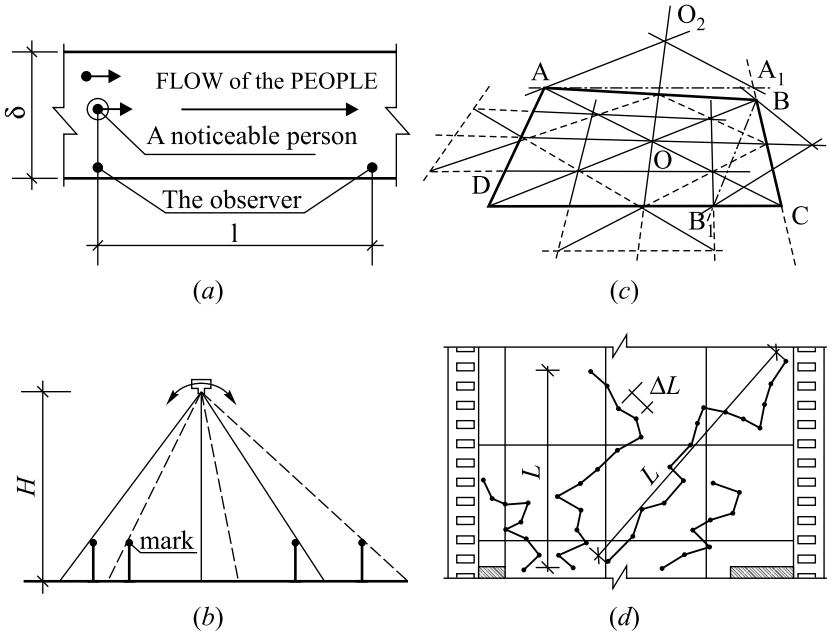


Figure 2. Methods of fixation of the data in full-scale observations and experiments: (*a*) visual, (*b*) movie-photo, (*c*) registration of perspective distortions, and (*d*) example of analytic analysis of pedestrian flow filming.

Historically, the visual method was the first one (Milinskii, 1951). The de-merits of this method are obvious: the accuracy depends on the subjective qualities of observers; limited practical utilization (with low density of flow and with relatively small width of route sections); impossibility to reproduce the "pictures" of people's motion in a flow in order to make an accurate analysis, etc. That is why in 1962, the movie (photo) method was firstly adopted (Predtechenskii *et al.*, 1964), which became the main one for all future investigations. However, the implementation of the described methods is limited due to the limited area of visible zone because of the vertical lens' position of a camera. Other angles of lens' axis cannot be used, because it is impossible to determine visual distortions, due to the perspective.

The utilization of some special methods (Grigoryants and Podolnyi, 1975) helps to get rid of these limitations and to make the area of implementation of movie-photo method wider (Aibuev, 1989), especially on long parts of routes or video-recording of pedestrian flows in restricted areas while conducting actual observations (Isaevich, 1990).

The utilization of modern video-recording devices helps to reduce the cost of actual observations due to lowering the expenses on buying and developing miles of highly sensitive movie film.

From the scientific research' point of view, the fixation of an observed "picture" of a flow of pedestrians gives a possibility to obtain quite objective results, to increase accuracy and details of situations under analysis, because it is possible to repeat a desired number of times either the general dynamics of a pedestrian flow or individual behavior of people in it. With such techniques in the same available time about 10 times more, the results on parameters of pedestrian flows under actual observations in buildings of different types and on pedestrian routes of city territories are obtained, as compared with visual observations. Exact numbers are 35,000 versus 3,600; the latter number was obtained mainly during the researches led by Milinskii in 1946–1948.

In Figure 3, a classical example of an experimental survey being an imitation of forced pedestrian flow of maximum density in a specially-constructed transforming hall is shown (Kopylov, 1974). The necessity of this experimental setup was explained by the impossibility

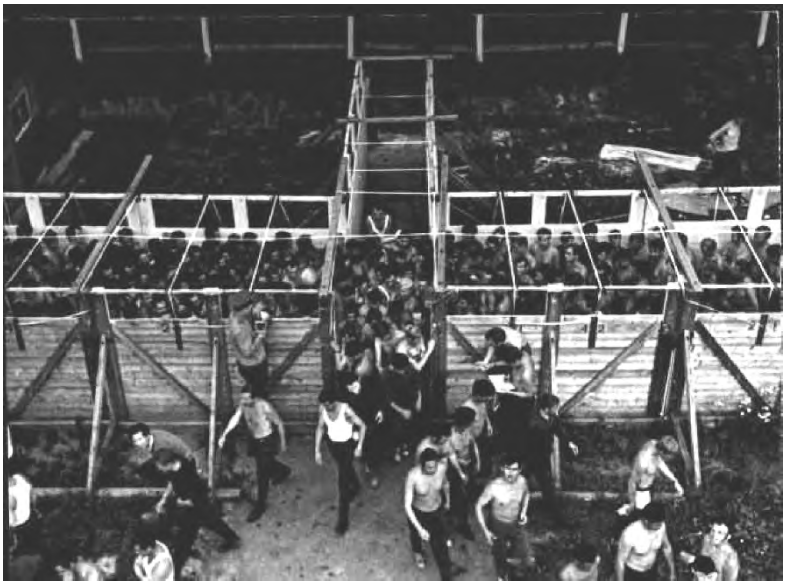
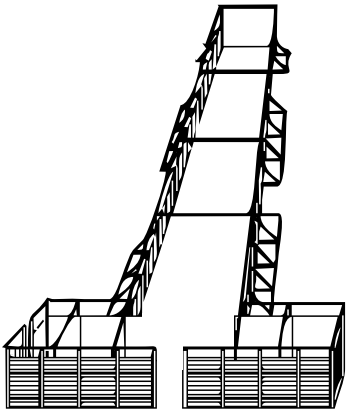


Figure 3. Experimental setup of transforming arena.

to make such a survey in reality with full recording of specific phenolmena of forced pedestrian flows, which can occur in extraordinary (alarm) situations in buildings. The transformation of the experimental hall made it possible to change the width of corridors and openings from 0.8 to 3.0 m with gradation of 0.2 m. Due to the possibility of the transformation, a great number or planning schemes with different combinations of their geometrical parameters were obtained (Figure 4).

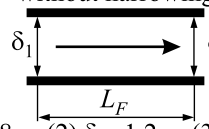
The pedestrian flows were formed with servicemen of Fire Guard Troops aged 25 to 30 and with students of Higher Fire Engineering School of Ministry of Home Affairs of the USSR aged 18 to 25.

The physical stressing of the traffic process under the high density of the flows was additionally made by special “retaining” groups of people at the ends of passages. They produced a physical pressure on people, who moved along the passages in pedestrian flows with given density.



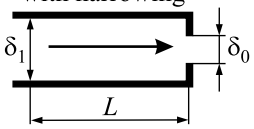
(*a*)

1. Horizontal part of a route without narrowing



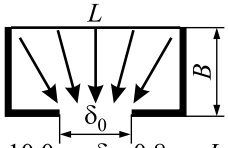
(1) δ_F=0.8 m L_F=9 m (2) δ_F=1.2 m L_F=9 m (3) δ_F=2.4 m L_F=15 m

2. Horizontal part of a route with narrowing



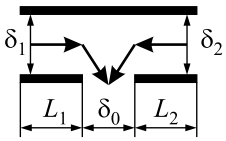
(4) δ_F=1.2; 2.4; 4.8 m. δ_0=0.8 m
(5) δ_F=2.4 m; δ_0=1.2 m; L=12 m
(6) δ_F=2.4 m; δ_0=1.6 m
(7) δ_F=2.8 m; δ_0=0.7 m
(8) δ_F=2.8 m; δ_0=1.4 m

3. Horizontal part of a route with free formation of a foot traffic flow near an entrance



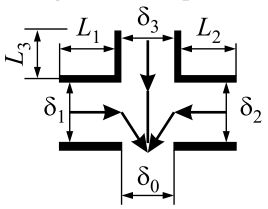
(9) B=10.0 m; δ_0=0.8 m; L=12 m

4. Horizontal part of a route after joining of two separate flows



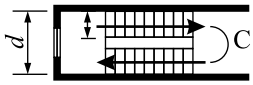
(10) δ_1=δ_2=1.2 m; L_1=L_2=6 m
(11) δ_1=δ_2=2.4 m; δ_0=1.2 m; L_1=L_2=6 m

5. The above case, with motion after joining of three separate flows



(12) δ_1=δ_2=δ_3=1.2 m; δ_0=0.8 m; L_1=L_2=L_3=6 m
(13) δ_1=δ_2=2.4 m; δ_3=1.2 m; δ_0=0.8 m; L_1=L_2=L_3=6 m

6. Half turn (dog-leg) stair



(14) L_F=1.8; 1.2 m;
B_{st}=0.3 m; H_{st}=0.15 m
C=1.5 m; d=2.4; 2.6 m;
N=11 steps

(*b*)

Figure 4. Experimental research investigations of pedestrian flows: (*a*) scheme of a transforming arena, and (*b*) planning scheme, studied for the transformation of flow in the arena.

The construction of the transforming hall made it possible to place a special overhead co-ordinate grid and to place special marks with 1-m spacing, which helped to determine the exact position of a movie-camera. All the observations were doubled with the aid of eight independent observers, equipped with chronometers and counting machines.

To increase the accuracy of filming, each participant of the experiment was supplied with number tags, fixed to their uniform hats. During this experimental study, more than 1970 measurements of pedestrian flow density and of people's velocity in it were obtained.

To compare the information obtained with possible pedestrian flows actually existing, more than 3,000 data were obtained. These were collected as results of actual experimental observations in situations of stable pedestrian flow with increased psychological and physical stress: on subway stations during morning rush hour, near huge Moscow department stores, where more than 1,000 people used to gather near the entrance just before the time of opening and on Moscow stadiums after football competitions.

Unannounced evacuations from buildings and observations of pedestrian flows with artificially taken types of participants (like school pupils during research on subway station) can also be considered as experimental research.

On the other hand, the study of pedestrian flows of different age groups of pupils in school buildings is an actual experimental observation, because these flows fully conjunct to the functional processes and maintenance terms of the building.

However, the empirical data obtained with different techniques during actual observations or experimental studies illustrate dependencies and rules, which exist in any pedestrian flow and rule the behavior of participants and the main parameters of the motion.

4. Pedestrian Flow Structure

In this context, the history of description of the structure of pedestrian flow and its parameters is very interesting. Nearly all give an identical description:

> "…The position of people in a pedestrian flow (along or across it) every time is uneven and frequently is occasional. The distance between people constantly changes and it causes local squeezing,

which later on disappear and appear again…"; "…A pedestrian flow usually has a longitudinal cigar-like shape. Avantgarde and arrieregarde parts of a pedestrian flow have few people, which are moving faster or slower, as compared with majority of people in a pedestrian flow…"; "…That's why for ALARM situations, it is necessary to take into account so called "spreading" of flow and, therefore, gradual changes of its density" (Predtechenskii and Milinskii, 1969; Figure 5).

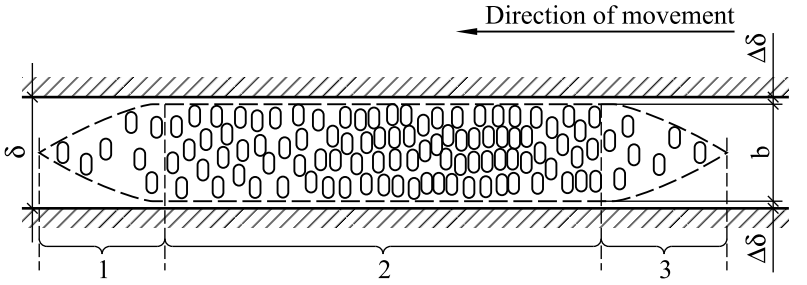


Figure 5. Structure of pedestrian flow: *1*—head; *2*—main part; and *3*—rear part of the pedestrian flow.

Some researchers, however, consider model structures as "elementary streams," i.e., rows of people, moving in column one behind another, assigning conventional lanes for their movement. Others admit to interpret streams of people in calculations as a rectangle with uniform density of people in it and the same speed of their movement. And there are specialists, who tend to substitute streams of people by streams of other physical substances, whether it is water or a viscous liquid, or a stream of dry or metallic particles in a magnetic field. Having satisfaction from a kind of similarity of the pictures of these streams, obtained by them from modeling, as created by their imagination of the abstraction of a stream of people, they do not consider important studying the entity of the substituted original. Yet, if the first two approaches are the product of difficulties of the research and reproduction of the real process, and are stages of its cognition, then the third approach is an easy way of computer 'game' on the basis of already known laws, although useless for this case. It all leads to deceit of a credulous consumer, who will build his/her protection system upon such concepts.

In these attempts to describe and model in a way the real process, we have to say: as usually, practice is a criterion of truth resulting in actual observations of streams of people.

5. Results of Actual Observations and Experiments

Observations of main dependencies among parameters of a stream of people and dependence of velocity of movement on its density, carried out by various researchers in different countries, give qualitatively an identical picture. In diagrams (Figure 6–8), there are results of 69 series of observations and experiments, containing about 25,000 simultaneous measurements of values of velocity and density of the stream.

As one can see, empiric dependences of these series show the common character of the relation between density and velocity of a stream of people for movement in different ways in buildings with various destination. For a quantitative description of each of these dependencies, there have been used mathematical formulas of different complexity, as a rule, of polynomials of the best approximation from fourth to second degree (Predtechenskii and Milinskii, 1969). Selection of such type of approximation of a dependency fully matches the situation, when researchers do not know the meaning of the discovered connection between phenomena and the regularity of their influence. Such description is not enough, though, for forecasting the possible development of the process, when the influence of factors, which determine the derived relation, will be different from its recorded realization.

6. Theoretical Developments

Much time has been spent on purposeful concentration on knowledge of psychophysics, psycho-physiological theory of functional systems, informational modeling of emotional states, mathematical theory of nonantagonistic games, theory of probabilities and mathematical statistics has been needed, in order to establish the regularity of the discovered relation between parameters of streams of people (Kholshevnikov, 1983). For now, there is an understanding of the movement of people in a stream as a random process and related to it a description of the dependence between velocity and density of a stream of people

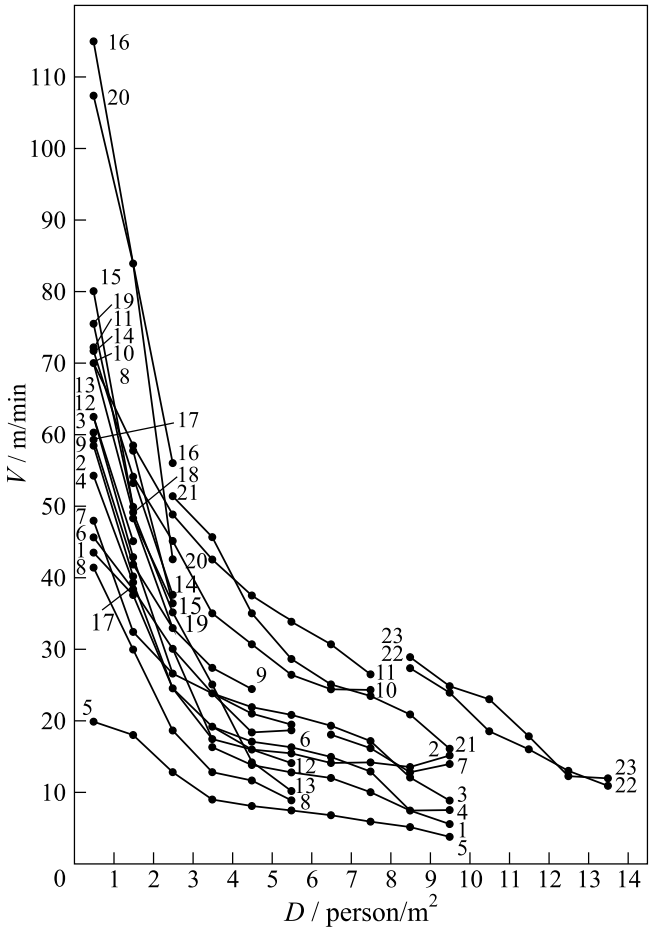


Figure 6. Empiric dependence of velocity of a stream of people on its density for horizontal movement: Type of buildings: theatres, cinemas—1, 5; universities—2; industrial—3; transport structures—4, 13, 14; sports—6; other—7; trade—8; schools: senior group—9, middle—10, young—11; Streets: shopping center—12; transport junction—15, 16, 18; Industrial units: 19; Underground stations: 20, 21; Experiment: 22, 23.

as elementary random functions. Apparently, such a model of a stream of people is the one most suitable to specify the above description of its real structure.

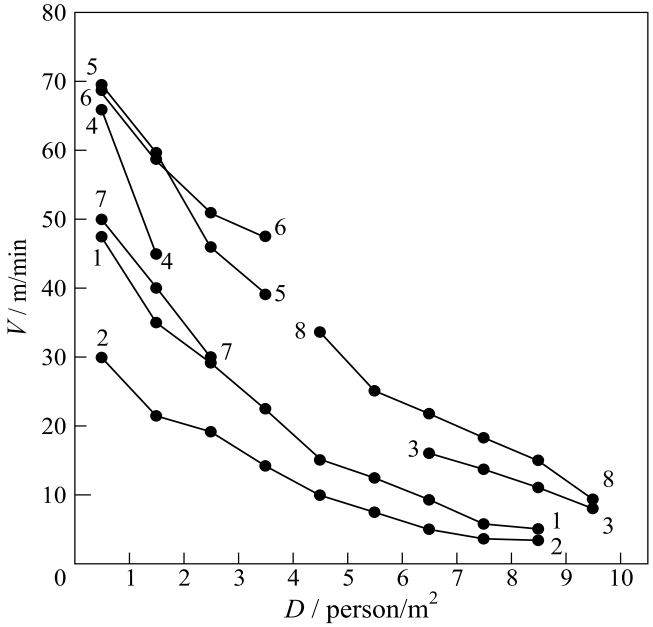


Figure 7. Empiric dependences of velocity of a stream of people on its density for movement downstairs: Type of building: multipurpose—1; sports buildings—2, 3; universities—4; schools: middle group—5, young group—6; Street: transport junction—7; Experiment: 8.

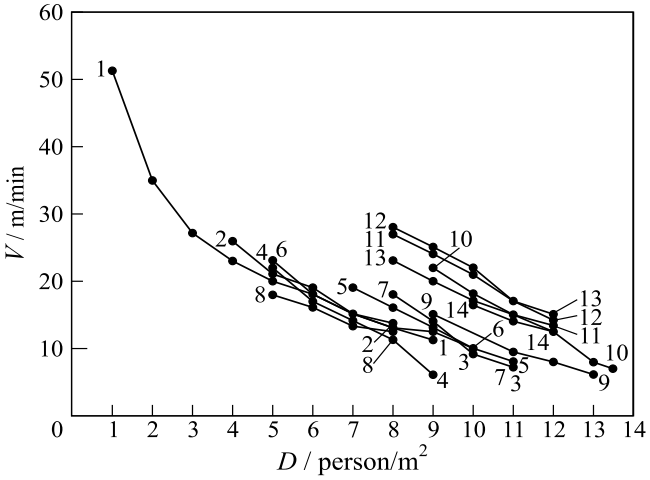


Figure 8. Empiric dependences of velocity of a stream of people on its density for movement upstairs. Type of building: multipurpose—1; retail buildings—2 to 4; sport structure—5; underground station—6 to 9; experimental—10 to 14.

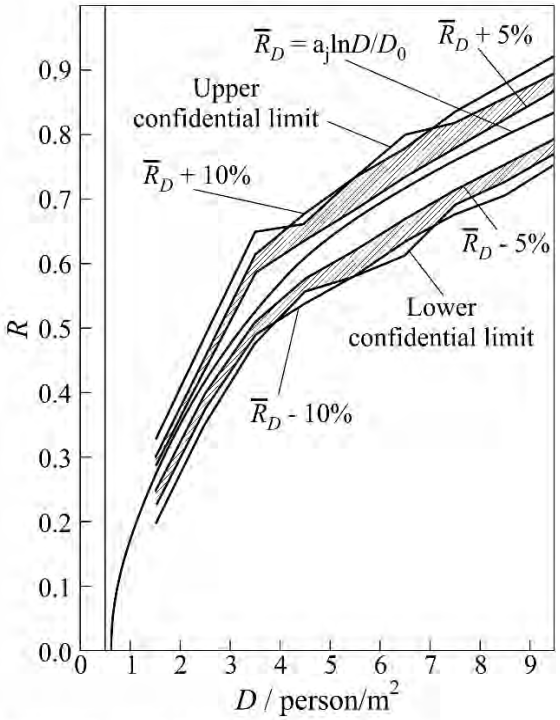
The dependency between velocity and density for any level of psychological tension of the situation, in which the movement of people takes place, can be written as the elementary random function:

$$\overline{V}_{D,j} = \overline{V}_{0,j}\left(1 - a_j \ln\frac{D}{D_{0,j}}\right)$$

that represents multiplication of a random value of velocity of the free movement by a nonrandom function (in parentheses). Here, $\overline{V}_{D,j}$ is the mean value of the flow velocity at density D while moving on jth type of route or pathway; $\overline{V}_{0,j}$ is the mean value of free travel velocity of people in the flow (at $D_i \le D_{0,j}$); a_j is the coefficient of adaptation of people to changes of flow density while moving on jth type of route; $D_{0,j}$ is the threshold value of flow density, till which free movement of people is still possible while moving on jth type of route (i.e., density does not influence the velocity of people's movement).

Velocity of movement of people in the stream and the stream in general depends not only on flow density and type of pathway. It also depends on physical abilities of people, who compose the stream; their emotional states, determined by both individual particularities of each participant of the movement and the overall psychological mood of the mass of people, who turned to be by co-incidence in the same crowd. The higher density of the flow and psychological tension of the situation, more common the psychological mood of the mass prevails over the individual awareness, as the ad-hoc composition acts as a single organism that appears for a short period of time.

This function shows that the influence of the level of psychological tension of the situation (conditions of movement) on the random flow rate can be evaluated by the dependency of the change of average velocity of movement of people on their emotional state in different conditions. Emotional state of people determines the category of their movement: comfortable, calm, active, increased activity. Movement at increased activity is expected during evacuation in emergencies. Intervals are established of probable change of velocity of free movement of people in a stream for each category of movement (Figure 9 and 10 with corresponding tables).

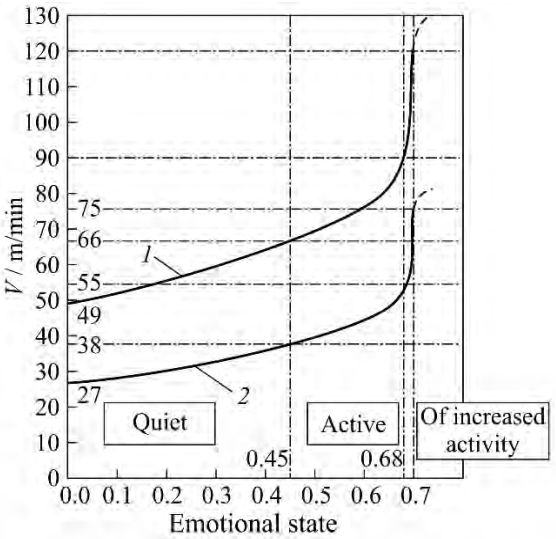


Values of a_i and $D_{0,j}$ for each route type.

Route type	a_j	$D_{0,j}$, person/m^2
Horizontal outdoors	0.407	0.69
Horizontal indoors	0.295	0.51
Door aperture	0.295	0.65
Stair downwards	0.400	0.89
Stair upwards	0.305	0.67

Figure 9. Regularities of change of flow velocity: measure of correlation as a function of the density of the stream of people.

Correlation dependences $R_j = \varphi(D)$ for all types of pathways have values of the degree of correlation (correlation coefficient) that exceed 0.98. Such high values of extent of correlation permit to evaluate the obtained dependences as functional. Overlaying the classification borders over the empiric curve dependences $V = \varphi(D)$ shows quite a satisfactory distribution of these curves over the categories of movement, which, according to descriptions, might correspond to real conditions of observation.



Categories of movement, emotional state level, and unimpeded travel velocity

Categories of movement	Level of emotional state	Unimpeded travel velocity V_0, m/s	
		Horizontal way, door aperture, stairs downward	Stairs upward
Comfortable	0.00	< 0.82	< 0.45
Quiet	0.45	0.82–1.10	0.45–0.63
Active	0.68	1.11–1.50	0.64–0.92
Of increased activity	0.70	1.51–2.00	0.93–1.25

Figure 10. Regularities of change of flow velocity depending on level of emotional state while moving: *1*—horizontally, through openings, downstairs; and *2*—upstairs.

The stochastic nature of the stream of people required development of corresponding models of movement.

7. Modeling the Movement of Streams of People

The history of research of streams of people contains different models (from verbal descriptions to analytical relations and their computer realizations). Though establishment of regularities of change of streams' parameters and of the structure while moving, as well as developing possibilities of using computers have encouraged development of new approaches to reproduction of the dynamics of this process.

Established dependency of velocity of movement of a stream of people on its density repeatedly proves the relevant feature of level of its density as noticed in observations. Up till the specific value ($D_{0,j}$), the density of stream does not have a great influence: people move freely, according to physical and emotional states. As density increases, the rise in density has more and more influence up to the liberty of movement of people in a stream: The stream, straightened or congested, at growing mutual reciprocate force of people on each other. This attains in some crowds such extent that it leads to compressive asphyxia. Respectively, we will have two models: one of free and one of straightened movement.

Models of free movement in a stream admit multiple options of simulation of individual movement of people, but the common criterion of their correctness is their conformity with results of observed statistics of real streams: distribution of people over the length of the pathway and by quantity of people coming into the considered section of the pathway (flow) at different moments of time. By using probability theory, distribution parameters of the velocity of moving people are easily derived. The stochastic model of free movement (Kholshevnikov, 1983, 2000) is given in Figure 11.

Modeling of straightened or congested movement requires registration of changes of parameters while crossing borders of adjacent segments of the route, permanent transformation of parts of the stream, its possible spread and creation of accumulations. A simulation model developed for this purpose (Kholshevnikov, 1983, 2000) describes the states of stream on discrete (elementary) segments of the pathway, in which it is divided, in consecutive periods of time.

Applying the computer program of the model, calculations are performed at different values of $V_{0,j}$ from the start of its probable change or in preset periods of time of modeling. These seek probable values of $V_{D,\,j}$ at density values of the stream of people, established in a considered segment of the way at that moment. In any case, statistics are obtained for parameters of interest on any segment of the evacuation way, particularly, the density distribution of values of time for ending the evacuation on the assessed route. Such approach permits to obtain a probable evaluation of conditions for ensuring the safety of people during evacuation: its time appropriateness $t_{\text{evac.}} \leq t_{\text{given}}$ (time of evacuation is shorter than the permitted one), and disembarrassment $D_i \leq$

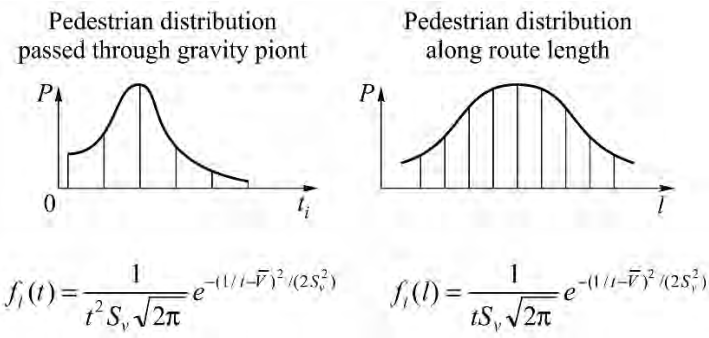


Figure 11. Stochastic model of free movement; *t*—time, *l*—length, *S*—standard deviation in velocity of the stream *V*, *P* — probability.

D_{acc} (density of stream on any segment of the route remains lower than the density at an accumulation of people).

8. Analysis of Adequacy

Correctness of research always requires an analysis of adequacy of the obtained results compared to real situations. Therefore, existence of regularities between parameters of stream of people, established according to data recorded in a database, has been also checked in repeated observations (Aibuev, 1989; Kholshevnikov and Dmitriev, 1989; Isaevich, 1990). Figure 12 shows diagrams of flow density impact on pedestrian travel speed on stations and transfer nodes of subway stations at different periods of its operation. Given results clearly indicate that established laws are correct and also properly represent respective categories of movement, according to established classification.

The correctness of the established regularity of change of velocity has been also proven in the performed series by including for the first time observations of groups of disabled people (Shurin and Apakov, 2001). Complex check of the correctness of the established regularities and movement models of streams of people are the subject of research of the real dynamics of size of streams of people (quantity of people, moving through controlled sections of the communication pathway in consecutive moments of observations) and its modeling. Examples, taken from the wide variety of investigated people movements at a factory premise before beginning the work shift (Aibuev, 1989) and in a passenger hall of a subway (Isaevich, 1990) are shown in Figure 13–15.

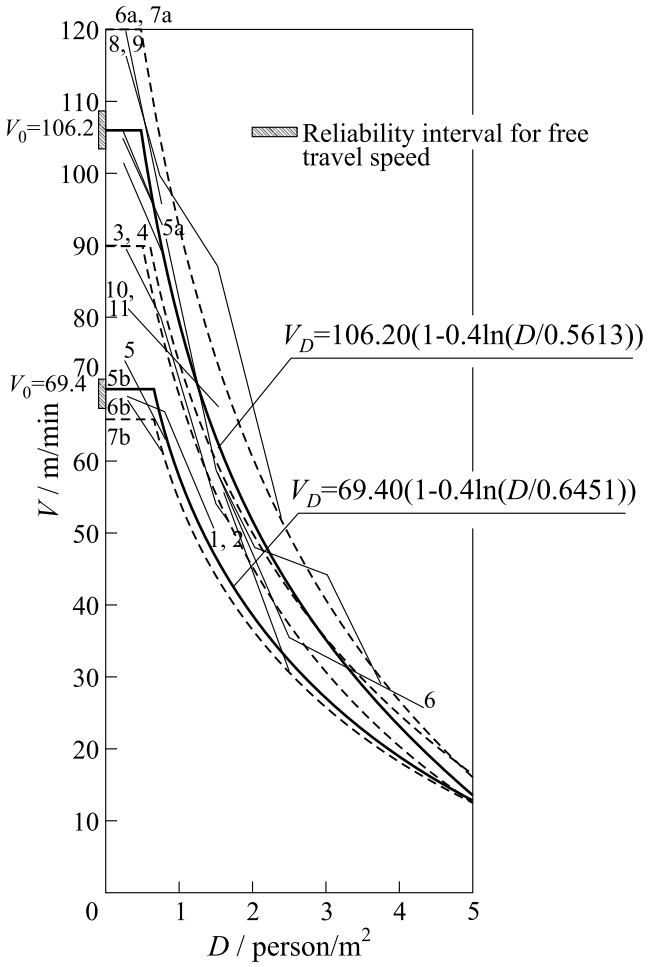


Figure 12. Experimental verification of the velocity change regularity of a stream of people as a function of density while moving horizontally in a Moscow subway at peak-hour (movement of increased activity, top line) and outside rush hour (active movement, bottom line): 1, 2, …—number of tests.

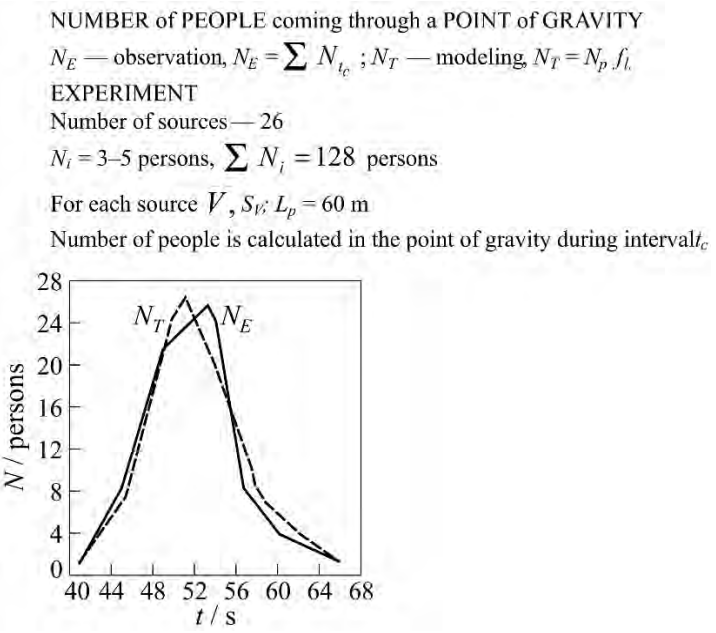

NUMBER of PEOPLE coming through a POINT of GRAVITY
N_E — observation, $N_E = \sum N_{t_c}$; N_T — modeling, $N_T = N_p f_l$
EXPERIMENT
Number of sources — 26
N_i = 3–5 persons, $\sum N_i = 128$ persons
For each source V, S_V; L_p = 60 m
Number of people is calculated in the point of gravity during interval t_c
28
24
20
16
12
8
4
0
N_T
N_E
N / persons
40 44 48 52 56 60 64 68
t / s

Figure 13. Free movement of people at a factory premise from a multitude of sources (crews of city public transportation) to one flow (factory gate).

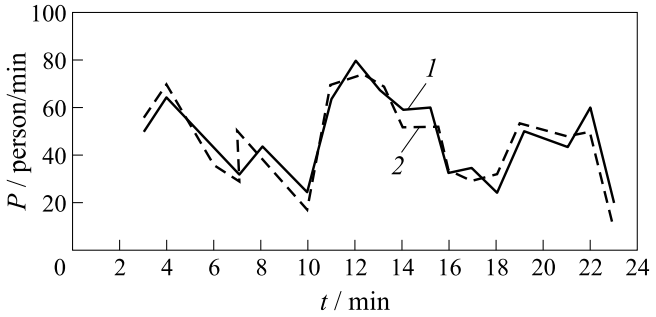


Figure 14. Dynamics of coming into a stream of people that are 100 m away from the source: *1*—observation, and *2*—modeling.

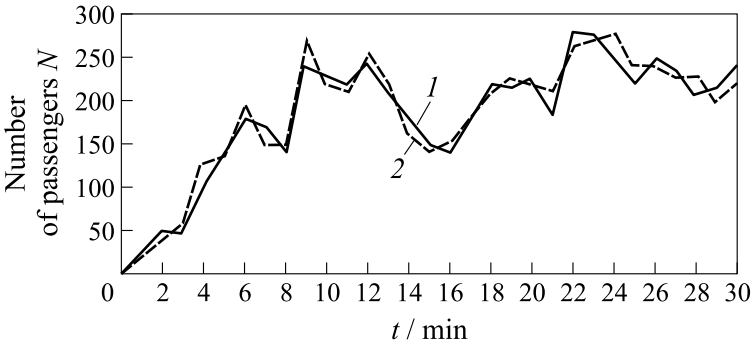


Figure 15. Variation of quantity of people that go through the cross section of the pathway in consecutive periods of time, in the example of passenger hall of the subway: *1*—observation, and *2*—modeling.

9. Discussion

1. An evidently high degree of adequacy of flow modeling as a circumstantial process of reality became the basis for the use of the results applied in regulation for the size of evacuation ways and exits (Kholshevnikov, 1999) and in calculating the time of evacuation of people while estimating a permissible level of impact of the hazards of fire (USSR State Standard 12.1.0004-91).
2. However, only the determined (calculated) dependency between the parameters of flow and the simplest correlation of kinematics of their movement was used. Such limited use of the determined relations is not only due to the level of competence of "regulatory" officers, but also to the nonreadiness of a wide range of specialists to re-organize their mind so radically. The technical provision of architectural and building design was also not ready for this. The requirement: "possibility of people's evacuation independently from their age and physical health…" "appeared" much later (Russian Building Code SNiP 21-01-97*, clause 4.1). The realization of the requirement dictates an evident necessity of modeling (regulation) of flow as a circumstantial process. However, it remained to be a nice slogan for a long time, not buttressed by possibilities providing its execution. Only recently competent authority managed to make a first step in their realization (Moscow Building Code MGSN

4-19-2005, appendix 16.2 “Basic Calculating Provisions of People’s Due Time and Unimpeded Evacuation”).

3. Ignoring a possible flow structure and the stochastic principles of dependencies between its parameters leads to incorrect definition of the possibility of provision of safety during people’s evacuation. For example, as determined by the USSR State Standard 12.1.004, the calculation of the time of people’s evacuation cannot correspond to a probability value $P = 0.999$, in case the calculation is carried out with average parameters of flow velocity, i.e., practically at its simplest structure. The consideration of variability of flow structure requires considering velocity as a circumstantial parameter. Then, the value of calculated evacuation time corresponding to the value $P = 0.999$ established with taking into consideration the influence of people of various age and physical health in the structure of the flow will be much higher (approximately, one and a half times, see Figure 16).
4. Not only is flow of people a circumstantial process, but also the distribution of hazards of an emergency situation has a stochastic character. Underestimation of these peculiarities of real processes causes self-deception while estimating time of people due to evacuation which is rather vividly illustrated by diagrams is shown in Figure 17.

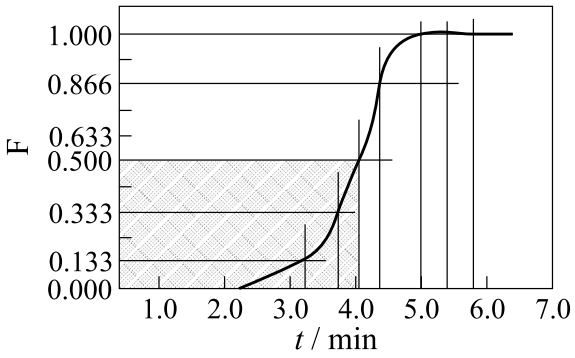


Figure 16. A graph of calculated cumulative probability of people’s evacuation as a function of time within a range from 2.2 to 6.34 min. In the dark area, an average values of the velocity of people’s movement in a flow is assumed. (USSR State Standard 12.1.004.)

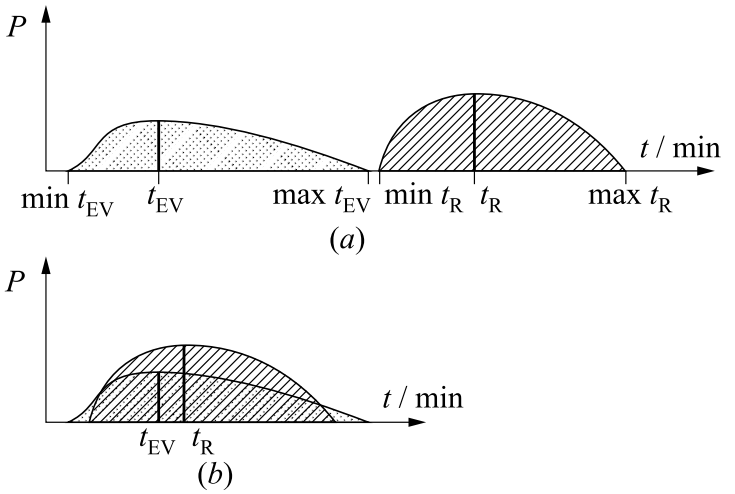


Figure 17. Illustration of provision of conditions of time due to people's evacuation: (*a*) at a real development of evacuation processes ($t_{EV} = t_{PREEVAC} + t_{TRAVEL}$) and hazards of fire ($t_R$), described by densities of possibilities distribution of the time of their achievement $P(t)$; and (*b*) at determining description of these processes, ignoring real (possible) character of these processes (correlation between only average values $t_{EV} < t_R$).

5. To provide for people's safety, their evacuation should not only be in due time, but smooth as well—without people crowding at the way out with greater density than at the maximum possible intensity of movement. Consequently, the probability of an event "people's safe evacuation," $P(C)$ is a multiplication of probabilities of evacuation in due time $P(T)$, and of evacuation in a smooth mode $P(D)$, so that $P(C) = P(T) \times P(D)$. It seems to be evident, but we have never seen this evident correlation to be taken into account while estimating risks of provision of people's safety in buildings and constructions.

6. Operation of modern, in particular, high-rise buildings and structures is impossible without the use of internal transport for people's movement. However, "evacuation ways … should not include elevators and escalators" (Russian Building Code SNiP 21-01-97*, clause 6.24). Isn't it an immoral decision to place people where they cannot get into and cannot get out without elevators and escalators, and then forbid them to use these means for the rescue of their lives? The European technical community, organizing joint

commissions, is only thinking "Can we permit it?" The answer is definitely: if we cannot permit it, then we should not build such monsters. We analyzed possible ways out from the current dilemma (Kholshevnikov, 2005; Kholshevnikov and Samoshin, 2006b). It is, however, necessary to use collective efforts to solve this paradoxical situation in a successful way.

7. According to the analysis of consequences of an emergency situation, fires, in particular, we might avoid many human victims with the start of evacuation in due time and with the right management, headed not by a principal from the central station, but directly by local personnel, constantly being in the building during its operation. Unfortunately, they have made only some first steps in this direction of research (Kholshevnikov and Samoshin, 2006a). Nonavailability of data concerning small children's evacuation is practically explained by nondevelopment of these problems. The solution of the problems posed requires collective and coordinated actions of all involved specialists and organizations.

10. Conclusions and Recommendations

Pedestrian flow is a process similar to human society. When society becomes more complex, this process also complicates. Each inhabitant of a city feels it in his individual daily experience. It seems that specifically the individualization of experience has shielded for a long time the awareness of the fact that each of us is a particle of an un-identified social-psychological phenomenon. Only from the top of the facts of natural observations, the outline of overall natural laws has started to take shape. Moreover, it is obvious that misunderstanding is putting in danger the preservation of our lives, which have become difficult to organize in an artificial environment of life activity.

At present, in many countries of the world, significant quantities of research material on people flow have been collected, which until now have remained nongeneric. So far, even the methods of carrying out nature observations and presentation of empirical data remain ununified. Meanwhile, scientific research (Grigoryants and Podolnyi, 1975) shows that incorrect use of observation methods can lead to 15 percent error in the result, while incorrect use of statistics, as it was already

noticed long ago (Kimble, 1982), can lead to “miracles”. Today, it is time to form an international unified database.

The general methods of analysis of model adequacy of movement of people in situations under different conditions as occurring in practice are absent. Going in the right direction will be difficult, but already today, it is time to block the substitution of man with particles of abiocoen[1]. Today, there is no need for this, since the theory of streams of people has enough possibilities to provide a model analysis with “human factors”. Still, it is necessary to widely involve research psychologists and physiologists, specifically the ones who could pass on the knowledge of their research not on academic level, but adapted to practical needs of the researched process, taking, for example, psychophysics. The target of the final work in these directions consists of the development of harmonized combined models of movement of people in different situations, including the stage of evacuation in emergency cases.

Today, in the examination of questions on ensuring security of people during evacuation, a strange situation exists: the normative documents and models suggest the conception that “People need to evacuate themselves (self-rescue) before the situation reaches critical levels which would inflict severe and lethal damage.” This kind of approach relieves architects and designers of new buildings and technology from any responsibility. Indeed, they owe the people to provide security against the effects of hazards during the time necessary for their evacuation, proceeding from the condition they are in and their physical possibilities. The first correct step in this direction in Russia has been already made: the norms of projection of high-rise buildings in Moscow city (Moscow Building Code MGSN 4-19-2005, appendix 13.2) require that the time of operability of the automatic systems of complexes, communications system and information should be “not less than the time of evacuation from the building.”

[1] Term from ecology: A nonbiotic habitat.

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SPATIAL DATA INFRASTRUCTURE AND GEOVISUALIZATION IN EMERGENCY MANAGEMENT

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Abstract: Support for an emergency management (EM) is one of the important requests for contemporary cartography. Map use demands high flexibility during emergency situations and variety of outputs according to changing situations, requested scope of decision making, and various users involved. Electronic maps are offering more flexible possibilities than traditional analogue maps, but nowadays, despite huge data sources for EM are Geographic Information Systems (GIS) based, still many cartographic interfaces are even less efficient copies of former analogue maps. At the base of this analysis, the focus on the role of GIS, geovisualization, and sensor technologies in emergency management is overviewed. Global description of positional accuracy, projection handling, geodata harmonization, and quality management for EM are described.

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Keywords: SDI; WSN; emergency management; geovisualisation

1. Introduction

Many countries around the world build spatial databases as parts of state spatial data infrastructure (SDI) and foster activities (INSPIRE[1], GMES[2], etc.) also on the international level. These databases are built for control and decision making processes support in state government institutions including support of an EM.

Support for the emergency management is one of important roles of geospatial data management including monitoring methods. Spatial data infrastructure usage during emergency situations is demanding highly flexibility interactions according to situation dynamic, scope of decision, making and various users' group involved. Most of decisions are spatially relevant and based on spatial information. Data management, data analysis, and data visualizations are offering more flexible possibilities for EM.

In our paper, we would like to make an overview of contemporary situation of research dealing with sensor monitoring and spatial data management and visualization for EM based upon experience from two projects WINSOC and GEOKRIMA.

2. Emergency Management and Spatial Data Infrastructures

The growing need to organize data across different disciplines and organizations and also the need to create multiparticipant, decision-supported environments have resulted in the concept of SDIs. Spatial data infrastructure encompasses the policies, access networks, and data handling facilities (based on the available technologies), standards, and human resources necessary for the effective collection, management, access, delivery and utilization of spatial data for a specific jurisdiction or community (Mansourian *et al*., 2005). Using SDI as a framework and a web-based GIS as a tool, EM can be facilitated by providing a better way of spatial data collection, access, management, and usage. Ongoing pan-European activities on SDI are directed towards the environmental sector (INSPIRE) and full employment of EM issues in SDI is a vital proposal for the near future.

Existence of SDI creates an environment enabling a wide variety of users to access, retrieve, and disseminate guaranteed spatial data in an easy and secure way. In principle, SDIs allow the sharing of data, which is extremely useful, as it enables users to save resources, time, and effort when trying to acquire new datasets by avoiding duplication of expenses associated with generation and maintenance of data and their integration with other datasets. Spatial data infrastructure is also an integrated, multileveled hierarchy of interconnected SDIs based on collaboration and partnerships among different stakeholders.

3. User Requirements Analysis

In order to assess and develop an effective geographic support for EM users requirements have been collected based on public materials published by ongoing European 6th Framework Programme projects (OASIS, OPERA, WIN), national projects (T-maps, 2004; Obrusník, 2005; Nesrsta *et al*., 2005), and extensive questionnaire in the Czech Republic. Further specified requirements are presented as a non-exhausted selection of all above quoted sources. Three main areas of generic users' requirements can be distinguished:

- *Interoperability*. The challenge of sharing information is complex: it requires understanding which information is useful, the format and who owns or controls it. Functional emergency spatial management system is to provide a technical solution that will allow sharing both geographic and nongeographic information, whilst controlling which part of the information is shared and with whom it is shared.
- *Networks*. Compared to public radio networks, the private radio networks are slower, and sometimes (for analogue networks), with a lower acoustic quality, barely supporting data transfers, etc. However, they are reliable, especially during an emergency operation, and that remains a fundamental requirement for general EM as well as for spatial applications.
- *Applications*. Tools that are used are still very basic: voice, e-mails, texts and short message services (SMS), faxes, telephones, and paper maps. So, the initial requirements focus on a simple system that will allow tracking of the vehicles and the teams in the field, access to external databases, having consistent and real-time

display of the situation, exchanging information with the people in the field, managing the resources and their planning, storing information on their activities and the emergency operation and retrieving information form internal and external databases.

Further specific requirements are listed which are considered to be visually depending, have certain spatial reference, or play a key role in geospatial management support (generic architecture and interoperability, security issues, information and communication infrastructure).

Among the most important requirements, the following can be named:

- *Open environment* compliant with existing infrastructure and systems in EM and able to share information with both new and existing legacy systems. Compliancy with existing legislation and security issues are highly accented.
- *System flexibility and scalability* for all levels of EM (local, regional, country, international). Hierarchical organization and implementation of EM information systems is a must.
- *High-quality communication infrastructure* ready to accommodate different communication tools (phone, fax, e-mail, video, SMS, teleconferencing) and assure their interoperability. Comparable or better quality in comparison with public networks is expected.
- *Information and system interoperability*—basic requirements for all levels of control and management. Risk-proof and compliant information exchange must be assured during the overall EM cycle.
- *Intelligent information sharing*—shared situational awareness is required and commended. Common situation picture must be available in different (hierarchical) level of detail in order to be compliant with user's context. Bulk information sharing and distribution can lead to information congestion and illegibility. Delivery of relevant information in appropriate format and the right time for the user is the key demand.
- *Security*—information confidentiality and security must be assured during the emergency situation. Therefore, authorization and authentication services are strongly required and rule based user's attitude for data handling is recommended.

- *Decision support tools and services* for EM. Among the most important are the planning tools (route planning tools, navigation services, and evacuation) and knowledge base access tools (biological and chemical substances, radiation, and common operation procedures), and predictive modeling tools.
- *Common terminology and ontology*—this issue is of a key importance for cross border and large-scale emergency operations. Interdisciplinary multilingual thesauri should be developed not only to unify the key words and phrases, but also their common meaning, understanding, and usage in EM.

Above listed user requirements can be considered as the high level demands on the EM systems functionality and architecture building blocks and their specific parts must be kept in mind during the process of geospatial support development. Present results of Geokrima and WINSOC projects have showed increasing importance of on-line access and transmission of field data into the EM command centre.

4. Geoinformatics and Cartographic Support in Emergency Management

The aim of geoinformatic and cartographic support of EM system building in the technical and technological parts is to ensure on-line accessibility to spatial databases of basic topographical and thematic data for all EM participants who need it as well as to create corresponding visualization's system of saved data and given operational process and be adequate of given types of users.

4.1. GEOGRAPHIC INFORMATION USED IN EM

Two basic sources for a geographic support of EM are used. The first sources are *basic topographic databases* containing all common important geographic objects and phenomena and their common properties from given territory. The second sources are *thematic databases* with supplementing information, mainly, about thematic properties of geographic objects from bases databases. The whole geoinformation system comprising both parts is called *the Integrated system of EM (ISEM)*.

From an EM principle results that no EM subject is allowed to change anything in ISEM data content with the exception of on-line

actual data collection during emergency situation solution or directly in the field. Competent state authorities and organizations are responsible for EM main data sources and guarantee their quality and correspondence with valid legislature.

According to Talhofer (2004), each digital geoinformation (DGI) has in certain level of generality following functions:

- *Information function* expresses DGI's ability of fast and reliable provision of information on position and basic features of the entered topographic subjects and phenomena in the area of interest.
- *Function of model* expresses DGI's applicability in model role for derivation of geometric or other relations of the topographic and other subjects and phenomena and their characteristics.
- *Function of source for mathematical modeling*, designing, and planning, applicable to the cases that use DGI to make future action intent or to design a work to be done.
- *Function of autoimmunization* in implementation process control of designed and planned projects. This function applies to position finding on move (ground or air), co-ordination or surveillance of a large number of moving objects (air traffic control, air surveillance in a sector region, vehicle movement tracking, and so on), traffic or other construction control and monitor.
- *Illustration function* expresses DGI's ability to illustrate situation, communication traffic such as in the HQ intranet, and others.
- *Function of source* for derivation of other types of GIS and maps and for cartographic purposes.

All functions are detectable in ISEM (either in a whole system or in their separate parts) and all geographic support should respect them.

4.1.1. *Basic Topographic Database*

The basic topographic database is guarantied by state mapping agency, duly maintained and regularly updated in order to comply both accuracy and precision demands of EM. Parts of a public administration are main users of this database including emergency system and its using is given according to law, e.g., Government Regulation N^{o} 430/2006 (Government Regulation N^{o}430/2006) in the Czech Republic.

A conceptual model of basic topographic database is defined to satisfy many users having various demands and EM subjects are only parts of them. Therefore, database content generalizes user's requirements to fulfil more of them. In Talhofer (2004), it is described one method of requirements evaluation. Many state or private organizations use basic topographic database like a foundation for own thematic data and information.

The database content and location and attribute accuracy have to agree to a mandatory rules usually corresponding to international standards (DIGEST-FACC, OGC, etc.). No EM subject changes anything in database content.

Two basic topographic databases created by state organizations are in the Czech Republic—*ZABAGED*, product of *the Czech Office for Surveying, Mapping and Cadastre* (COSMC), and *DMU*, product of the *Geographic Service of the Czech Armed Forces (GS CAF)* (Svatoňová, 2006). Data from both databases can be supplied in WGS84 and UTM projection. Unfortunately, their contents are not simply changeable despite of modeling one area. Many objects are defined differently including their field classification. According to law, both databases can be used in EM and this situation could affect misunderstandings during intervention if co-operating subjects use different source databases.

4.1.2. *Thematic Database*

The environmental nature in the vicinity of a possible accident is a "passive participant" of such event. Both the *individual components of the landscape* (i.e., air, water, ground, biota, geological environment with relief, energy balance, etc.) through their parameters and *the landscape as a whole* (system) are involved in the running processes. They respond to the accident both individually and systemically, i.e., conditionally according to the response of other components. Due to objective complexity of each process, the evaluation of impacts and the prognosis of development can be based upon the preliminary assessment of participation of individual components of the environment and its parameters, and consequently, the alternative synthesis according to the possible scenarios can be carried out.

Much information useful for EM is collected from the social economic sphere in various organizations. Very important is information about critical infrastructure whose disturbance should cause considerable damages to health or property. Areas of responsibility division

and position of separate fire brigades, police, and medical emergency service, etc. units are also very substantial, mainly, for decision making processes during given intervention. Not all thematic information integrated in ISEM has to be geoinformation. Information about chemical substantives and their properties, and inhabitants register are examples of them.

Parameters that are not included in basic topographic database is necessary to find in *thematic databases*. Many various organizations (governmental or private) are responsible for thematic databases creation and unfortunately, no one method of their conception is used. Thematic databases are built either on a basic topographic database or have own topographic foundation, spatially, in case of databases with less resolution (in position and in thematic properties too).

Thematic databases usage is generally in two ways. In *the first case*, object's properties form thematic databases, which are useful, are directly set into given objects of basic topographic database. In *the second case*, thematic databases stay in their native format like an external source.

The *usability of basic topographic and thematic databases* which are available *in the integrated databases of the crisis management* is secured by the conversion procedure of the saved data content to the purposefully aimed digital product—*Expert Purpose Interpretation* (EPI). *The* EPIs can be generated for all main types of crisis's situations in advance according to an ontology of standard operational procedures as well as direct in time of crisis situation solution—for example, tendency of the ground to pollutant infiltration at the site of accident. This expert interpretation can be visualized at the corresponding management level (Figure 1). So, the crisis management bodies gain their imagination how to progress subsequently after intervention which rescues the lives and health of the participants in the event.

In EM, there are many subjects which have to co-operate during solution of crisis situation. Many of them use geodata and geoinformation in a digital form or like classical maps, but very frequently in various resolutions, data format, and systems of geodata visualization. EM subjects form different professional branches and usually have own laws and rules what data have to be used in emergency situation.

But this state could lead in considerable misunderstandings and in consequence, cause bad decision. To prevent them from mistakes doing

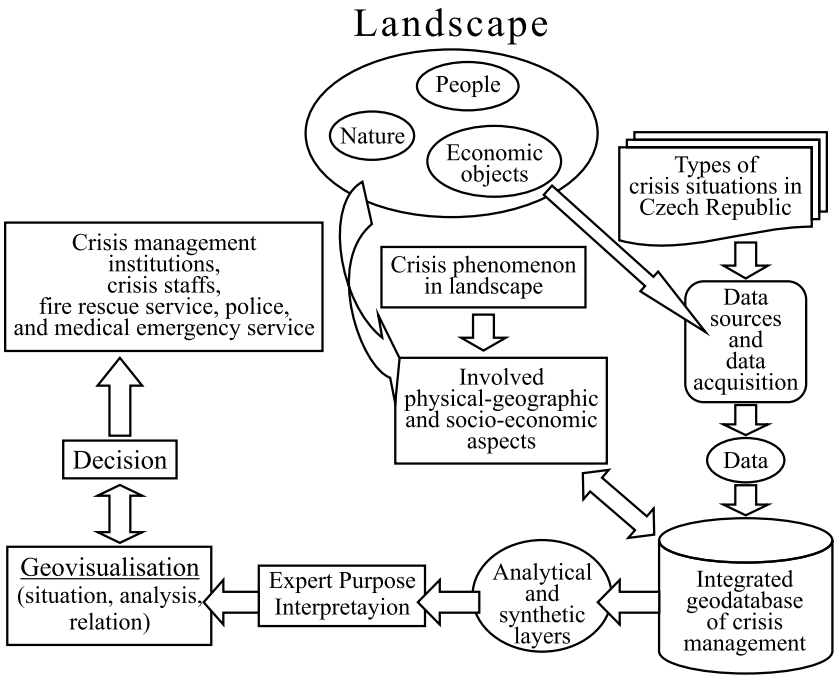

Figure 1. The diagram of selection, processing, and geovisualization of the data for decision-making in the crisis management.

during co-operation between EM subjects, all subjects could accept a base standardization of geographic information and their thematic properties. It is possible to find a common data and common data properties of all EM subjects and *an area of intersection of information* (AII) define (Figure 2).

All data in AII can be fully standardized and added by properties necessary for adaptive cartographic visualization methods application.

4.1.3. *Position Determination in an Emergency Management*

All objects and phenomena saved in EM geodatabases have to have uniquely determined position. This definiteness is given by standardized geodetic datum and, eventually, use cartographic projection.

Continuous positioning service is necessary to have in the EM geodatabases (Kratochvíl, 2006). *Global navigation satellite system* (GNSS) guarantees requirements concerning accessibility, coverage,

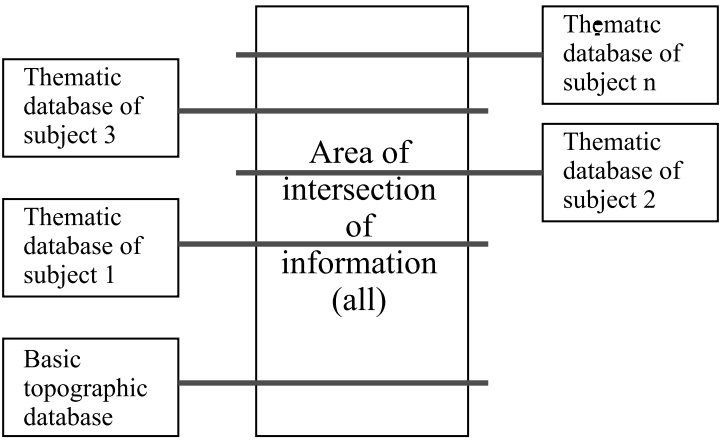
Thematic database of subject n
Thematic database of subject 3
Area of intersection of information (all)
Thematic database of subject 2
Thematic database of subject 1
Basic topographic database

Figure 2. Area of Intersection of information.

precision, and reliability of position determination. Three GNSS's are in operation or in final development:

- *GPS–NAVSTAR* (Global Positioning System) administrated by US government. Only GPS is in full operation since 1996 and fulfil EM demands;
- *GLONASS* (Global'naja Navigacionnaja Sputnikovaja Sistema) administrated by Russian government. System is instable and does not fulfil EM requirements. Only more than one half of all planed satellites (24) is active (14—in September 2007);
- *GALILEO* developed by EU members should supply both previous systems with more sophisticated technology enabling wider usage in practical life including EM. Their full operation setting should be in 2010, but project is delayed.

Inertial or quasi-inertial positioning systems as well as GSM networks is possible to use for location determination instant of GNNS. But both types have same limitation resulting from their construction and technologies and therefore are often added by GNNS receivers.

Except technical devices for position determination, *analogue maps* stay very useful for EM. Classical maps are usually easy available, cheap, readable, light, etc. No electric power is necessary to use a classical map.

Four datums are possible to use in the Czech Republic—ETRS, WGS (ITRS), S-JTSK (civilian datum) and S-1942 (former military—Pulkovo 42) according to Government Regulation N^{o} 430/2006. In resolution of 1 m, the two first datums are changeable, but civilian and former military not (Figure 3).

The similar situation could occurs during crises situation solution on state's border if subjects from different countries can co-operate and each team works in own national datum.

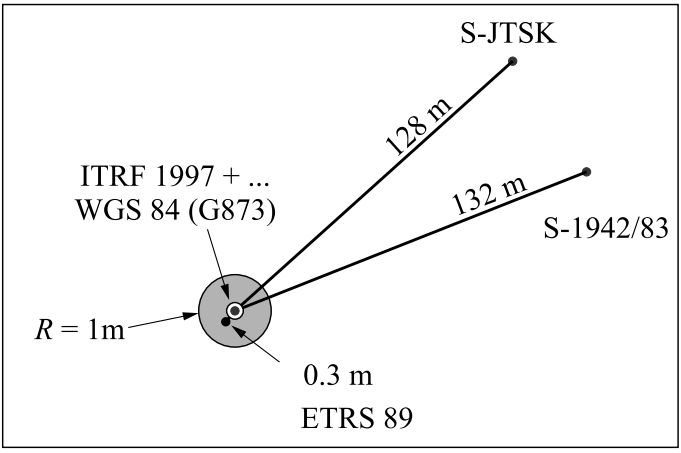

Figure 3. Position differences among mandatory datums in the area of CR. (Kratochvíl 2006.)

4.2. SPATIAL DATA AND ONTOLOGY IN EMERGENCY MANAGEMENT

Providers and users of geographic data specify fairly different models for same objects depending on their notion and with regards to their specific application, point of view, and understanding of the reality (Giger and Najar, 2003). Taking into account this fact, accuracy and relevance of geospatial data are terms that are not assessable in general: the same object, represented in different ways, is possibly relevant for one application, but not for the other. Accuracy and relevance, however, depend on a specific view of the reality that is consistent within one geospatial information community. This kind of "subjectivity" has to be

considered properly when evaluating accuracy and relevance of spatial data sets (Pundt, 2005).

For disaster management, this means that data must meet conditions that are specific for a (one) disaster situation. Considering this fact, first tackled by Pundt (2005), it is even more important to develop specific contexts. The crux is that in time critical disaster situations no time is left for users to look on data quality properties, or metadata. When spatial information is needed within a few minutes to save lives or to avoid large damages, the data must be available in time, and users must be sure that they can trust the data. This makes formal ontologies an interesting approach to support data and object identification. While current practice tends to use "generic" geographic view with a limited possibilities of automated (=optimized) visualization rules, the use of ontologies could improve and quicken the relevancy of geographic data. Ontological approach is closely related to geospatial information communities (GICs, Pundt, 2005) collecting and maintaining spatial data sets. Data are intended for specific purposes and tasks carried out by such GICs. The GICs define real world objects as classes, entities, attributes, properties, relationships, uses, etc., using their specific terminologies. This means that the database objects reflect specific semantics, not necessarily clear and understandable to users outside that information community. This situation has been described and partly solved in Open Geospatial Consortium (OGC) Discussion Paper "Style management services for emergency mapping symbology," where the problem with interoperable geographic data sources and multiple visualization is described as in Figure 4.

In Figure 4, people (e.g., first responders and emergency management personnel) use "Map viewer clients" to dynamically generate and view maps of emergency incidents, critical infrastructure, and other related information. The users of the system may, however, represent a wide range of organizations and "information communities" engaged in different emergency management activities including support for emergency detection, preparedness, prevention, protection, response, and recovery. While all communities may use the same sources and standards for accessing geographic data, each user-community may have specialized rules for cartographically representing emergency-related information on maps. In many cases, the disparate user-communities may mandate use of styling rules and symbol sets that are

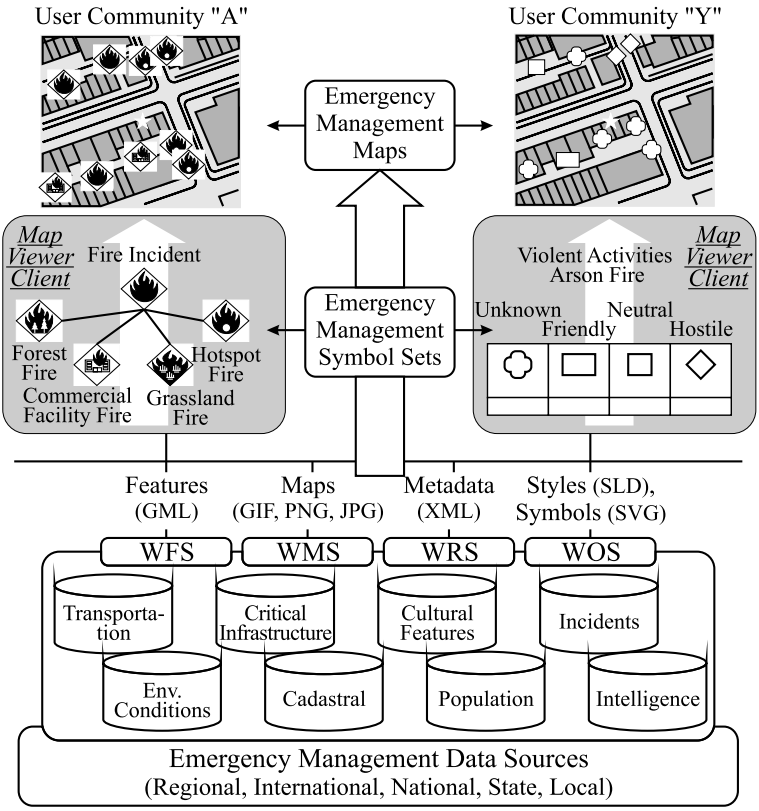

Figure 4. Operational context.

designed specifically for generating map products tuned for their intended use in supporting the specialized mission of their users. Thus, in Figure 4, the users in "User-community *Y* " (e.g., first responders) may be accustomed to viewing maps with incident symbols presented one way (presumably meaningful to their mission) and users in "User-community *A*" (e.g., incident recovery planners) another way.

The challenge presented above can be mitigated somewhat to the degree that cartographic styling rules and symbol sets can be standardized and adopted across the user-communities. Nevertheless, there will always be information communities with different (possibly contradictory) requirements for map portrayal that result in the definition and use of different styling rules and symbol sets for map production.

The EMS-1 Architecture is intended to enable interoperability, flexibility, and re-use through a common framework of service interfaces and encodings for styles, symbols and associated metadata.

Being on the way toward the semantic web, ontologies are seen in a very pragmatic manner: converting machine-readable into machine-understandable information by providing well-defined meaning for the content distributed within the www, which is the main goal of ontology (Vögele and Spittel, 2004). If computers become able to understand information, they should also be able to evaluate, to a certain extent, the relevance of the data in a given disaster situation (Pundt, 2005). To make ontologies usable within a GIS or modeling framework, a proper design and formalization of ontologies is required. The design phase includes a decision to which category ontology belongs. Fonseca *et al*. (2002) provide a categorization of ontologies that has been adapted for the case of disaster management.

Figure 5 shows that there is not only one general ontology, but various, and that the ontology belongs to a category that describes its universality or degree of relation to a specific domain. A general ontology of geometric objects describes the objects concerning their spatial extent and geometric form. Specific domain ontology describes the objects including their semantics; the latter defined in a language of a geospatial information community. It is such a domain ontology that gives the objects a meaning within a specific context. At this stage, it is clear that it is not intended to argue for the development of "an (one) ontology for disaster management." But ontologies can help to overcome the problems that occur due to semantic heterogeneity. The only way to support information access and sharing is to make data sets understandable for humans, as well as computers. This goal is supported via formal ontologies. In future, an increasing number of ontologies will appear, especially domain xontologies that capture the knowledge within a particular domain (e.g., electronic, medical, mechanic, traffic, urban and landscape planning, or disaster management).

Andrienko and Andrienko (2006) use the domain ontology as one of the corner stones for intelligent visualization system development. In their opinion, the role of emergency management domain ontology is to built up a system of general notions relevant to the domain of emergency management and the relations between those notions. This includes:

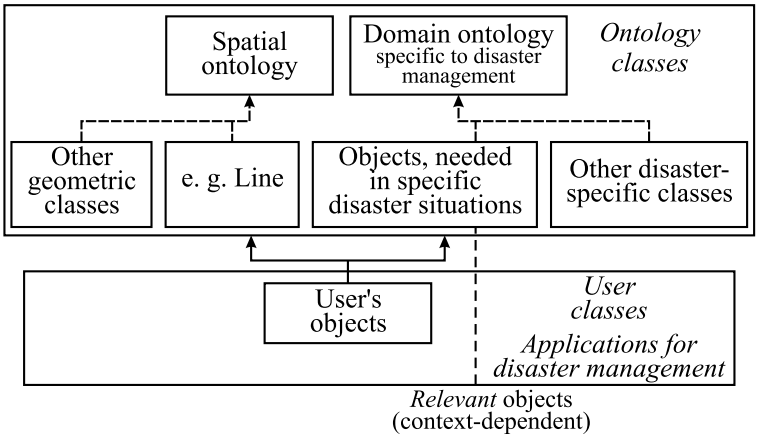

Figure 5. Categorization of ontologies and relevant objects. (Basic model from Fonseca *et al*. (2002), modified.)

- Various types of events such as fire, flood, or chemical contamination, their elements (agents) such as flame, heat, water, or hazardous substances, and the effects that may be produced by these agents such as ignition, detonation, destruction, or contamination
- Types of objects entailing latent dangers and the agents that may activate those dangers. For example, petrol facilities are hazardous in case of ignition while an electric transformer station is a source of risk in case of leakage of a flammable gas
- Various groups of population that may require help, their special needs, and types of places where these population groups may be present, such as schools, hospitals, or shopping centers
- Generic tasks that are often involved in emergency management, such as evacuation of people, animals, and valuable objects from the danger zone and
- Types of resources and infrastructure that may be needed for managing emergency situations, including people, teams, and organizations (e.g., a fire brigade or a bus company), transporttation means, roads, sources of power, fuel, water, and so on.

4.3. VISUALIZATION OF SPATIAL DATA

Several attitudes to the spatial data visualization (geovisualization) have been presented by Kohlhammer and Zeltzer (2004) and Andrienko and Andrienko (2006). The former is referred to as decision-centered visualization, which means the usage of problem-oriented domain knowledge for intelligent data search, processing, analysis, and visualization in time-critical applications. The objective of the later attitude called "intelligent visualization" may be formulated as "give everybody the right information at the right time and in the right way." This statement involves two aspects:

- A person or organization should be timely supplied with the information that is necessary for the adequate behavior in the current situation or fulfilling this actor's tasks and
- The information should be presented in a way promoting its rapid perception, proper understanding, and effective use.

The first aspect refers to the problem of the selection of the relevant information, depending on the situation and the needs, goals, and characteristics of the actor. The second part refers to the problem of effective preparation, organization, and representation of the information. Intelligent visualization supposes that both the selection of the relevant information and the subsequent processing, organization, and representation of the selected information are automated. Automation is achieved by applying the knowledge base technology into the visualization concept. This feature is considered by authors as the main differentiator between both concepts.

New concept of adaptive cartography has emerged in last years (Reichenbacher, 2003). Though originally used for mobile solutions, it has proofed viability in more general manner. Nowadays, electronic maps can be adapted to the requirements of a specific user so that the decision-making process of the user which is dependent upon the map information shall be facilitated as most as possible. The set of characteristics related to the user, the environment, and the purpose of maps is called a context, and the maps which can dynamically respond to the context are called adaptable maps (Kubíček and Staněk, 2006; Friedmannová *et al.*, 2006a).

Improvement of the visualization by adaptive cartography is focused on sufficient amount of information delivered just in time, instant

awareness of principal objects, real-time reclassification of multifactorial (parametric) geoobjects, simple symbology with easy perception, and user-centric visualization over shared distributed geo-database in compliancy with up-to-date technological standards.

Adaptability of cartographic representation can be considered from following viewpoints:

- *User level*—operational units, dispatching units and stakeholders need different scales, themes, and map extent, but over the same data.
- *User background*—different educational and map use bias.
- *Theme importance*—different features in map content and variable significance with changing emergency situation.
- *New phenomena*—new features reflecting the emergency status need to be inserted into map consistently.
- *Interaction device and environment*—various electronic visualization devices are used and they are also in interaction with environment which is influencing visibility and amount of information used.

Purpose of the context handling is to decrease time necessary for decision making. In case of spatial oriented issues is map natural medium for information storage and exchange. Efficiency of this information processing strongly depends on map use skills and also on ontological homogeneity of users' point of view. In real situation is necessary to count with high heterogeneity of users collaborating on spatial related tasks. Consequently, special map representation for every user is needed. Because is out of a technological possibility to create individual map for every person in any situation, more feasible is to create several user groups. Also situations are divided into certain amount of scenarios, covering the most common context combination.

The reaction on the context change is the change of the map content. Changes are related to the particular context attributes and are possible distinguish following cases:

- *Change of symbolism*—the most simple and the most common method of adaptation. The change is related to display capabilities, environmental conditions and user background or preferences. Typical implementation approach is creating symbols thesauri covering various user groups and devices.

- *Cartographic generalization*—quite complicated and time consuming issue. Generalization processes react on a change of purpose, changes of features significance, changes of the spatial extent and partially also on data transmission rate. Usually, amount of the features and features classes is reduced and also feature representation is simplified.
- *Change of cartographic method*—is related to the user background or to the purpose of the map. For users, unskilled in map reading, is profitable usage of less abstract and easier to interpretable methods.

In many cases, it is impossible to separate all three types of changes. Necessary change is usually a combination of all methods. For example, if there is requirement for presentation of highly specialized theme to public is imperative to adjust all aspects—simplify or even radically change symbolism, reduce content, and finally, use unequivocal cartographic method (Friedmannová *et al.*, 2006b).

4.3.1. *Dynamic Adaptive Visualization in Emergency Management*

Crisis management is typical case for the geocollaboration of heterogeneous user groups. There is possible to define very different groups varying in roles, skills, and knowledge. Every group is possible to describe by ontology, list of tasks, spatial extend of authority, and place of operation.

Research agenda covering issues of dynamic adaptive visualization for emergency management can be divided to several main tasks:

- *Integration geodata from various resources*—establishment of common reference base and automated transformation of geodata location and granularity according to source reference base and scale.
- *Transformation of prediction models*—real-time transformation of model results to be more readable for nonspecialist.
- *Automated generalization*—real-time reduction of map content complexity according to scale, purpose and territory characteristics. Approaches of multiresolution database and simple just-in-time generalization are combined.

- *Crisis management participant's ontology description*—point of view of different user groups is described and symbolism thesauri are created.
- *Symbol design*—according to device characteristic, cognitive research of perception in stress situations and existing standards and customs new symbol sets are proposed and evaluated.
- *Cartographic support for change recognition*—implementation of the visualization techniques, which can handle dynamics of the situation (change of object, its importance, movement, etc.).

Digital geoinformation and its visualized image is used not only in stationary systems but also in many mobile devices (GPS receivers, mobile phones, etc.) equipped with good quality displays (size, resolution, colours, frequency, etc.) enabling digital geodata visualization. From the point of EM view, mobile devices support communication between all participants of the EM event in horizontal (on the same level of decision making management) and vertical directions (communication with higher command). They enable data collection, visualization, communication with databases, and real-time data collectors such as sensors.

A stable, powerful, resistant, and accessible communication system is an assumption of useful mobile devices using. The communication system has to be supported by information and geoinformation systems ensuring dynamical change of geodata. Mobile devices are used by field staff members who work under time and psychical pressure and need up-to-date data and information urgently. Transferred information should be selective according to solved situation, unambiguous and understandable for all included active and passive users too. Finally, efficiency of transferred cartographic information perception is given by:

- Properties (attributes) of used geodata and geoinformation (their content, positioning and thematic resolution, quality, topicality)
- Suitable cartographic visualization method for used type of device
- Quality of data updating system as well as used communication and information system and
- Actual psychic stage of end-user given by his personal qualities, level of education, and stage of actual surroundings environment

Dynamic cartographic visualization tools can provide appropriate tools and solutions for realization of above mentioned reasons. *Dynamic cartographic visualization* is a variable system where cartographic language is used and map content is adapted according map scale, size of area of interest and context—a combination of visualized data, used hardware as well as social-cultural background and environment of end-users. Outline of the psychological theories and methods applications and functional-design approach to geographic visualization in the framework of interdisciplinary investigation is presented by Švancara (2006). Prime concern of psychological investigation is given in three main areas:

- Focusing: the personality of the solver of geographic information finding himself in the most critical predicament;
- Integrative evaluation of perception, cognitive style, executive processes and coping processes; and
- Implementation: optimal competency of the end users of geographical information.

4.4. TECHNOLOGICAL SUPPORT OF EMERGENCY MANAGEMENT

4.4.1. *Web Architecture*

An adaptive map development in a WEB environment is a fundamental demand on whole solution (Kozel, 2007). Web environment is built with four-tier architecture (data store including sensors measurement, map server, context service, and client) with possibilities to extend it into *n*-tier architecture. Adaptive map is created on client side; server side ensures context cartographic visualization process.

An advantage of *n*-tier architecture is division of technology into logical parts—layers. If is necessary to replace one layer, applied technology enables it without bigger problems. The replacing is better the more standardized communication system among other layers is used. Communication among layers is through questions and answers with maximum of standards using and is independent on various software platforms (MS Windows, Linux, Mac OS X, etc.).

Client pictures context map (no adaptive) by means of Web Map Service (WMS) browser, which communicates with a context service through extended WMS questions. More than one client is allowed.

Extended client is able not only to picture context map but also to carry an adaptive map on his web browser. The adaptive map communicates with an extended context service by the help of the context service. More than one extended client is allowed too.

Map server selects data from relevant data store on the basis of context service question and generates corresponding context map from selected data. Generated map returns to the context service and it gives it back to client. More than one map server is allowed.

Data store manages spatial data and provides them to map server. Usually, more than one data store is used. The data store could guarantee also access to sensors measurement, where data are automatically stored on the servers using WSE standard.

4.4.2. *Used Standards*

The importance of the standard procedures for communication were recognized by the OGC which is currently addressing an extensive set of interoperability initiatives and standards (WMS, WFS, SWE) and the OGC Working group on disaster management became active dealing with the emergency management relevant geospatial issues (critical infrastructure—CICE, emergency management symbols—EMS).

4.4.2.1 Web Map Service

An OGC WMS produces maps of spatially referenced data dynamically from geographic information. This international standard defines a "map" to be a portrayal of geographic information as a digital image file suitable for display on a computer screen. A map is not the data itself: WMS-produced maps are generally rendered in a pictorial format such as png, gif or jpeg. Web Map Service operations can be invoked using a standard web browser by submitting requests in the form of Uniform Resource Locators (URLs). The content of such URLs depends on which operation is requested. In particular, when requesting a map, the URL indicates what information is to be shown on the map, what portion of the Earth is to be mapped, the desired coordinate reference system, and the output image width and height. When two or more maps are produced with the same geographic parameters and output size, the results can be accurately over-laid to produce a composite map. The use of image formats that support transparent backgrounds (e.g., gif or png) allows underlying maps to be visible. Furthermore,

individual maps can be requested from different servers. The WMS thus enables the creation of a network of distributed map servers from which clients can build customized maps (Wikipedia, 2007).

4.4.2.2 Web Feature Service

The OGC *Web Feature Service* (WFS) Standard provides an interface allowing requests for geographical features across the web using platform-independent calls. Geographical features can be seen as the source data behind a map, whereas the WMS interface or online mapping portals like Google Maps return only an image, which end-users cannot edit or spatially analyze. The XML-based geography markup language (GML) furnishes the default payload-encoding for transporting the geographic features, but other formats like shapefiles can also serve for transport. The WFS specification defines interfaces for describing data manipulation operations of geographic features. Data manipulation operations include the ability to create a new feature, delete a feature, update a feature, and get or query features based on spatial and nonspatial constraints (Wikipedia, 2007).

4.4.2.3 Sensor Web Enablement

As the critical management is starting to be still more actual according communication with GIS tools, the OGC starts to release the *Sensor Web Enablement* (SWE) that should become a standard in integrating of variety kind of sensors into one communication language and well defined web environment. Open geospatial consortium SWE is intended to be a revolutionary approach for exploiting Web-connected sensors such as flood gauges, air pollution monitors, satellite-borne Earth imaging devices, etc. The goal of SWE is the creation of web-based sensor networks. That is, to make all sensors and repositories of sensor data discoverable, accessible and where applicable controllable via the www. Open geospatial consortium defines a set of specifications and services for this goal. Below are short descriptions of these services.

4.4.3. *Context Service*

A context service takes a question extended of given context from a client and on its base supplements WMS question next parameters relating, mainly, with symbology definition, map content, etc., so with

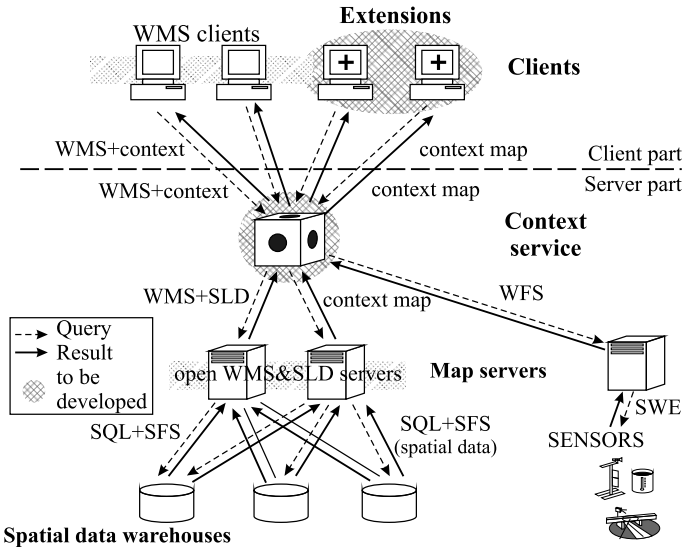

Figure 6. The technological support of EM GIS solution.

cartography visualization process. A standard *Styled Layer Descriptor* (SLD) is used for cartography visualization definition. A new created request WMS&SLD is sent to the relevant map server. Its answer in corresponding interpretation of map view is sent to the client.

The context service has to be able to communicate with clients and map servers. The communication with the client is through extended WMS question where extended part could be unstandardized. The context service also enables above standardized communication with the extended client, e.g., enable to inform his about context change possibility, to send him information about new context including list of WMS questions, etc.

A communication between the context service and the map server goes also on extended WMS question, but this extension could be standarddized by the help of SLD standard. Second possibility is to have direct access to data using WFS.

In Figure 6, there is presented whole technological support of EM GIS solution.

5. Sensors and Sensors Networks

5.1. SENSORS AND SENSOR NETWORKS

The future utilization of sensors technologies in crisis management will be mainly based on “Smart Dust” (SmartDust project overview) which is an emerging technology made up from tiny, wireless sensors or “motes.” Eventually, these devices will be smart enough to talk with other sensors yet small enough to fit on the head of a pin. Each mote is a tiny computer with a power supply, one or more sensors, and a communication system. To facilitate the development of smart transducers and promote its use in different control networks, the IEEE 1451 standards were created. With the objective of addressing the problem of the fragmented market, they set out to specify a set of common hardware and software interfaces between the smart transducers and the control networks. The goal is to allow the separation of the transducer’s project from the choice of the control network, promoting the development of network independent transducers (IEEE Std 1451.2–1997). The IEEE 1451 standards were developed to address the need for a common set of interfaces between transducers and control networks. The IEEE 1451 actually represents a family of standards that work for the same goal: define a set of common interfaces for connecting transducers to microprocessor-based systems, instruments, and field networks in a network-independent fashion. Network independence is accomplished through the division of the smart transducer model in two parts. One is the network independent module Smart Transducer Interface Module (STIM) that contains the transducers, its signal conditioning circuitry and a standard interface. The other is a network specific module Network Capable Application Processor (NCAP) that implements the interface to the desired control network and also implements the standard interface of the transducer module.

Sensor networks are receiving a significant attention because of their many potential civilian and military applications. The design of sensor networks faces a number of challenges resulting from very demanding requirements on one side, such as high reliability of the decision taken by the network and robustness to node failure, and very limited resources on the other side, such as energy, bandwidth, and node complexity. For this reason, many recent works on sensor networks have concentrated on the efficient use of the available resources, mainly,

energy, necessary to achieve the users' requirements. A critical aspect of a sensor network is its vulnerability to temporary node sleeping, due to duty-cycling for battery recharge, permanent failures, or even intentional attacks. Decentralizing the decisions is also strategic to reduce the congestion probability. Congestion around a sink node is an event that is most likely to occur precisely when a hazard situation occurs, in which case many nodes send their warning packets to the control nodes at about the same time.

A centralized approach may be vulnerable to failures of sink or control nodes. Furthermore, it requires, in general, the transmission from all the nodes to the sink node and this increases the probability of congestion. For this reason, it is useful to devise decentralized strategies that do not necessarily rely on the existence of a fusion center to derive a distributed consensus about the observed phenomena. Consensus may be also seen as a form of self-synchronization among coupled dynamic systems. It was shown how a population of nonlinear systems, linearly coupled through a general directed graph, is able to self-synchronize. Self-synchronization of pulse-coupled oscillators is proposed as a way to perform decentralized change detection. Self-synchronization is a mechanism that plays an important role in the distributed algorithms proposed in WINSOC. From an engineering point of view, the main question is whether this system is sufficiently stable to guarantee a proper functioning, in spite of the simplicity and potential unreliability of the single cell.

5.2. WINSOC CONCEPT

One of the projects that we are experienced with is *WINSOC*[3]. This project is mainly focused on establishing the wireless network, but also the publishing of observed data and communication between upper level sensor nodes data has been taken into the account.

WINSOC explores the possibility to develop a novel technology for Wireless Sensor Networks that has significant potentials for overcoming conventional technologies in terms of cost, size, and power consumption, The key idea of WINSOC is the development where the high accuracy and reliability of the whole sensor network is achieved through a proper interaction among nearby, low-cost, sensors. This local interaction gives rise to distributed detection or estimation schemes, more accurate than that of each single sensor and capable to achieve

globally optimal decisions, without the need to send all the collected data to a fusion center. The whole network is hierarchical and composed of two layers: a lower level, composed of the low-cost sensors, responsible for gathering information from the environment and producing locally reliable decisions, and an upper level, composed of more sophisticated nodes, whose goal is to convey the information to the control centers. The implementation of SWE interfaces into the WINSOC concept divides the sensors into different node levels. Level 1 nodes are simpler and smaller devices that will implement the WINSOC algorithm. Level 2 nodes are more complex and powerful devices that will be responsible for data collection from the lower level nodes. This node will be located "close" to the sensor itself, because of the possibility of communication between each particular sensor (bluetooth, wired LAN). On Level 1 node, there will be developed a wireless node for outdoor applications that can interface to external sensors through serial lines. Given the different types of sensors that are needed for risk analysis, a multidrop RS485 bus is advised. We are already using monitoring stations with sensors connected to a network node via an RS485 bus. These nodes are going to implement the WINSOC algorithm.

On level 2 nodes, there are suitable HW/SW platforms, where the web services will run. These platforms will implement, as functional libraries, the techniques of data extraction from the WINSOC network; these libraries will be used by the Web services to accomplish the task required from the client.

6. Pilot Scenario "Transportation of Dangerous Chemical Substances"

In order to test approaches of dynamic visualization and related technological solutions, a pilot user scenario "Transportation of dangerous chemical substances (DCS)" was elaborated in autumn 2006. The scenario was based upon the basic functionality with two initial blocks: "Normal operation" block and "Accident" block. Within these basic blocks, the following functions have been designed:

- In case of "Normal operation" when the transport vehicle exhibits no emergency conditions, two basic functions have been proposed:

- Monitoring of vehicle motion transporting DCS in the region on the overview with the basic topographic situation
- Information about the surroundings of moving vehicle where the possible elements of the critical infrastructure are highlighted according to the type and the quantity of transported DCS

- In case of “Accident”, i.e., when nonstandard behavior of the transport vehicle is monitored, the following basic functions have been designed (Figure 7):
  - Highlighted visualization of all objects and phenomena which can be potentially affected in the surroundings of the vehicle due to transported DCS (the context visualisation which relates to this substance) and
  - Automated information transfers to the Integrated Rescue System (IRS) control room about the vehicle position, its accident, the type and quantity of DCS transported access route to the place of accident

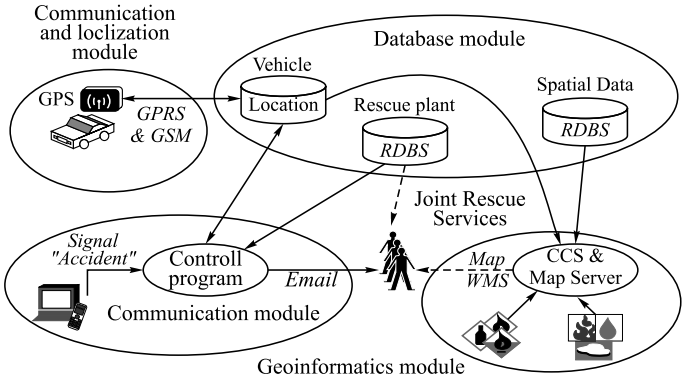

Figure 7. Transportation of dangerous chemical substances scheme.

The method of visualization was based upon the context representtation where the visual spectacular objects were only those objects which were in a range of the vehicle monitored, and additionally, which related only to the given type of cargo (specific chemical substance) and to the potential risk. The context was defined according to the type of accident and the thematic elements were assigned to each type of accident considering their risk.

The communication and information systems of all above mentioned modules were active over the complete time of the experiment. In case of a simulated accident, information about the accident origin and its position which was received from the localization and communication module was automatically sent to the preset addresses. The cartographic data was available via WMS reference web site which due to its open interoperability provided the map resources for a wide scale of Internet and even desktop applications. Brief and detailed information about the type and nature of DCS and the methods of protection against such substance received from the DCS database and from the methodical intervention sheets were sent at the same time to the preset addresses mentioned above.

7. Conclusion and Future Prospects

The authors concentrated on analysis, approaches, and solutions fostering wider usage of visualization in emergency management. Naturally, the fundamental item from which all processes start is existence of SDI which is not anymore only static sources of data but more and more getting new dynamic component. These aspects are closely connected with the possibility to add to the "static" data also those coming in real time from sensors, remote sensing sources, and other new technological equipments. Delimitation of so-called critical infrastructures is one of the key steps to find appropriate solution in emergency situation.

User requirements analysis and implementation are crucial for usage of new visualization approaches in the general EM processes. In the paper, main areas of users requirements are distinguished. Three fundamental ones: interoperability, network, and applications; and five additional ones: open environment, system flexibility, highquality communication infrastructure, information, and system interoperability, and intelligent information sparing. Very important is positional determination where systems like GPS–NAVSTAR, Glonass, and Galileo are opening new potentials of usage information and communication technologies, generally, and in visualization, particularly. Visualization processes are based on geoinformatic and cartographic support realized through basic topographic and thematic databases, following technological standards, and metainformation systems. Visualization

processes and approaches proposed and developed during Geokrima and Winsoc projects are based on the theory and practice of context mapping. Context mapping services were elaborated and defined on the basis of fundamental research of real users requirements. Standard compliant tools based on web services WMF and WFS are used for distribution, sharing, and visualization of the data for particular emergency situations. As the part of information and communication services, sensors and sensor networks are adapted for GIS and Web environment. Authors describe contemporary approaches in harmony with previous results of WINSOC project. There are shown examples of practical application based on the pilot study. Results are coming from the transportation of dangerous chemical substances at the territory of the Czech Republic. Paper is summarizing main usage presumptions of visualization based on SDI in EM. Authors supposed rapid development of all mentioned technologies in the European and global scales in the near future. Especially cartographic visualization will offer many new revolutionary solutions which will close a gape between scientist and decision makers at the EM situations.

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USING VIRTUAL ENVIRONMENT SYSTEMS DURING THE EMERGENCY PREVENTION, PREPAREDNESS, RESPONSE AND RECOVERY PHASES

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Abstract: In this paper, we review application of virtual environment systems to emergency management. Section 1 describes new possibilities that virtual environment technology offers. In Section 2, we analyze application of virtual environment technology to simulation and first responders training during the preparedness phase of an emergency. Section 3 discusses mobile augmented reality systems for first responders' equipment, navigation and three-dimensional (3D) geographic information representation, damage evaluation and reconstruction of buildings. Section 4 explains how virtual environment technologies provide visualization and decision support for management personnel. In the last section, we make some conclusions about current research in this field, present systems and future trends.

Keywords: visualization; virtual environment; emergency management; simulation; decision support; geographic information system; augmented reality

1. Introduction

Emergency management methods are constantly being improved by applying new technologies. Reliable, up-to-date and clear information is crucial for the success of an emergency response. Therefore information technologies are widely used during the emergency preparedness, response and recovery phases. In particular, visualization and Virtual Environment (VE) technologies have progressed rapidly in the last few years what opens up a new way for information representation.

Counter-terrorism has become one of the major tasks of emergency management after the tragic events of 9/11. At the same time, September 11th demonstrated the crucial role of visualization in emergency response activities (Delaney, 2002). The goal of this paper is to describe briefly the possibilities for VE technologies application to emergency management support.

Previously, specialists of several Fraunhofer-Gesellschaft institutes conducted research on emergency management support systems including a survey of experts on the technologies they used and lacked (Meissner *et al.*, 2002). The experts placed emphasis on the following aspects: communication and information management, optimization

and simulation, decision support, visualization, geographic information systems and development of training systems.

In this paper we review opportunities that VE technologies open as applied to emergency management. In Section 2, we analyze application of virtual environment technologies to simulation and first responders training during the preparedness phase of an emergency. Section 3 discusses mobile augmented reality systems for first responders' equipment, navigation and 3D geographic information representation, communication between rescue workers and a control room, damage evaluation and reconstruction of buildings. Section 4 explains how virtual environment technologies provide visualization and decision support for management personnel. In the last section we make some conclusions about current research in this field, present systems and future trends.

2. The Role of Visualization in Emergency Simulation

The governmental bodies paid attention to emergency analysis and simulation methods in attempt to make the public safer (see, for example, NRC, 2002).

Most of the emergency modeling systems is intended for solving the following problems:

- Forecasting, identification and modeling of an emergency with the aim to estimate its consequences and to choose the best response strategy
- Training rescue workers to behave efficiently in an emergency

Virtual environment systems can be used as a tool for information representation in both of these cases with different aims.

Management personnel need an efficient representation method for results of emergency forecasting and modeling, which can help them to estimate the scope of the threat and the pros and cons of possible response strategies. Participation effect is essential for rescue workers training.

2.1. A MODELING OF AN EMERGENCY

The four phases of an emergency are: Mitigation, Preparedness, Response and Recovery. One can create a model of an emergency during both the preparedness phase (to estimate possible consequences and evaluate response strategies) and the response phase (to forecast development of the emergency and choose the best response strategy). In the latter case, the decision has to be made in a short period of time. Moreover, a wrong decision and nonoptimal strategy may lead to catastrophic results.

Decisions made on the basis of analytical analysis are potentially dangerous (NRC, 2002; Cai *et al*., 2006). Models often are not perfect and do not take into consideration all significant factors. Moreover, formal models often imply a number of assumptions (which are sometimes incorrect) experts do not know about. Seamless interaction between experts and information system can solve these problems. But experts do not have enough time to learn an interface during an emergency so they need an intuitive one that VE systems offer.

Although most of emergency simulation applications deal with 3D models, VE systems are not widely used in this field yet. Nevertheless research laboratories started to implement VE installations step by step. For example, the U.S. Geological Survey (USGS) conducts research on tsunamis and earthquakes and visualizes the results in VE. Some of their models are available on the Web (USGS, 2005). In 2002, Southern California Earthquake Center implemented a GeoWall system (a low-cost 3D stereoscopic projection system). Now it is used in the LA3D project (SCEC, 2004).

In the Dutch–Russian research project (Kirillov and Pasman, 2004) VE was used for two purposes:

1. Visualization of the results of the 3D simulation of hazardous phenomena (Figure 1) and sharing data between project participants located in 14 different sites (12 in Russia and 2 in the Netherlands) (Lukashevich *et al.*, 2003)
2. Provision of advanced capabilities of user interface—simulation problem specification and initial data input for (i) risk analysis (Panteleev and Lukashevich, 2004) and (ii) building resilience (Roytman *et al*., 2003) assessment systems.

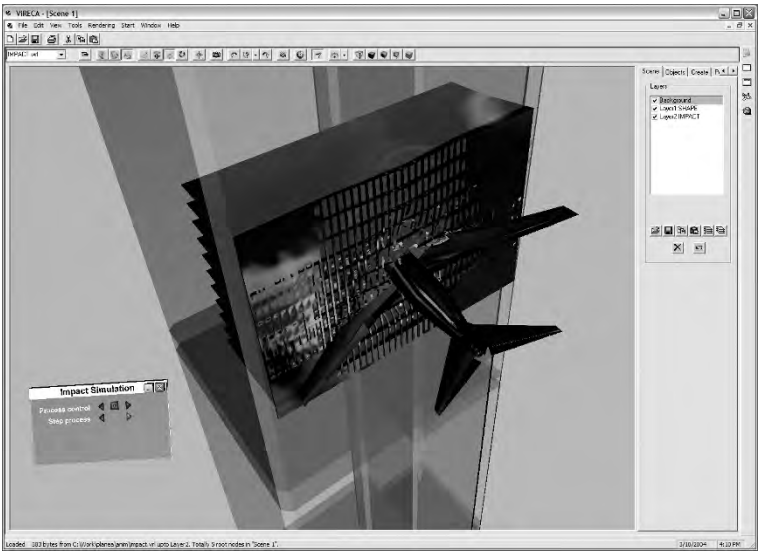

Figure 1. Visualization of aircraft-building-crash for data sharing between the ABC project participants (Kirillov and Pasman, 2004).

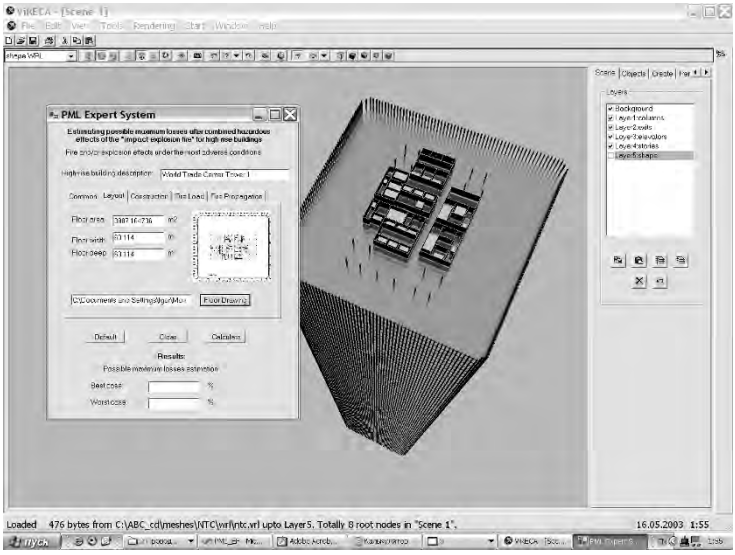

Figure 2. Problem definition for damage/loss simulation in risk assessment system using advanced capabilities of user interface of VE (Panteleev and Lukashevich, 2004).

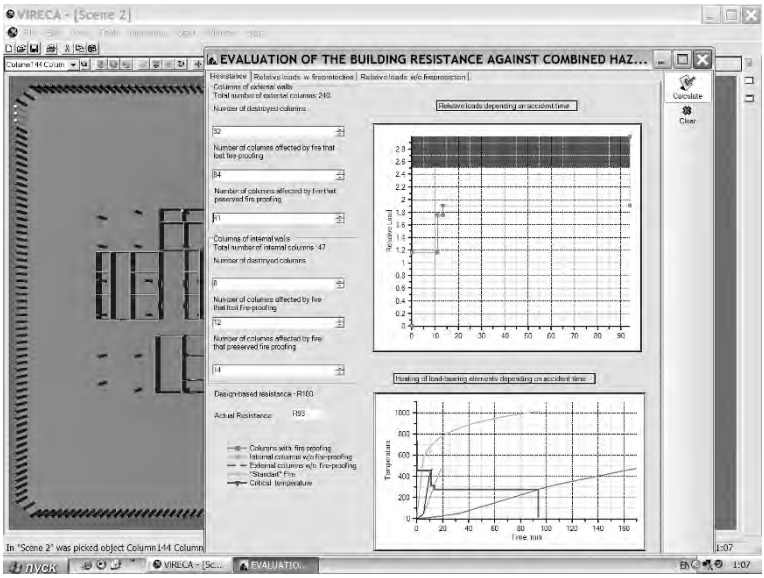
VIRECA - [Scene 2]
EVALUATION OF THE BUILDING RESISTANCE AGAINST COMBINED HAZ...
Resistance
Relative loads w. fireprotection
Relative loads w/o fireprotection
Columns of external walls
Total number of external columns: 240
Number of destroyed columns
32
Number of columns affected by fire that lost fire proofing
64
Number of columns affected by fire that preserved fire proofing
41
Columns of internal walls
Total number of internal columns: 47
Number of destroyed columns
8
Number of columns affected by fire that lost Fire-proofing
12
Number of columns affected by fire that preserved fire proofing
14
Design-based resistance - R160
Actual Resistance: R93
Columns with fire proofing
Internal columns w/o fire-proofing
External columns w/o fire-proofing
"Standart" Fire
Critical temperature
Relative loads depending on accident time
Heating of load-bearing elements depending on accident time
Calculate
Clear
In "Scene 2" was picked object Column144 Column
1:07

Figure 3. Bearing capacity simulation problem definition in building resilience assessment system using advanced capabilities of user interface of VE (Roytman *et al.*, 2003).

2.2. RESCUE WORKERS TRAINING

Virtual environment systems are widely used for education and training purposes as they provide an immersion in a virtual world where a user takes part in an action as a personage (Baturin *et al.*, 2007).

Simulators require more realistic visualization as compared to the systems described in Section 2.1 above since their primary task is to create participation effect. Development of realistic models of propagation of water, flame and smoke is especially difficult.

Simulators can be used both for rescue workers and ordinary people training, e.g. in case of fire evacuation (Ren *et al.*, 2006; NIST, 2006; Louka and Balducelli, 2001). Since real training is expensive, involves preliminary organization and can even be dangerous because of large crowds, it makes sense to use special simulators in VE. It enables one to teach fire evacuation procedures and teach about a plan of a particular building, evaluate the plan and clarity of the notations on the evacuation routes.

The Advanced Disaster Manager Simulator (ADMS, 2007) produced by Environmental Tectonic Corporation (ETC) is the most famous commercial product in this range. The U.K. Ministry of Defense, the International Fire Training Center of the United Kingdom and other organizations have implemented this system.

The drawback of training systems on the basis of VE technology is that it is not possible to train on a "real" landscape but rather on an abstract one. It seems reasonable to integrate training systems with common 3D geographic information systems (see Section 3.3).

3. ARS and GIS for First Responders

Rescue workers and firefighters have to orient themselves quite quickly in an emergency even though a territory is completely unknown to them. If rescue workers knew the territory before the accident, it might look different due to smoke and damages (Figure 4).

During the rescue operation after the terrorist attacks of September 11th, 2001, maps of the territory were prepared and printed in a large scale (Delaney, 2002). Of course, a large-scale printed map is better than none, but it is not the best way to provide rescue workers with geographic information. Electronic maps are much better. Still, they have a number of disadvantages:

Figure 4. Rescue operation after September 11, 2001. (Images courtesy of FEMA, photo by Michael Rieger.)

- They do not have an intuitive interface.
- They do not provide a suitable interface to instruct first responders in real time and to coordinate their actions.
- They are unsuitable for representing 3D geographic information which is sometimes essential.

By the second week of the rescue operation after the attacks of September 11th Emergence Mapping Data Center started the deep infrastructure project (Delaney, 2002) with the aim to create 3D maps of all underground structures (elevator shafts, communications lines, etc.). To sum up, we need a suitable interface to represent 3D geographic information to rescue workers and to provide communication between them and a control room. Augmented Reality System (ARS) provides such an interface. Augmented Reality (AR) is a technology based on the combination of real world and computer generated data. It is a particular case of Mixed Reality (MR).

Three-dimensional GIS is essential for effective navigation because it contains information about many-storeyed buildings, electrical and gas lines, etc. If 3D GIS had an AR interface then rescue workers would not have to compare territory around them with a map to choose a direction to move in, which saves a lot of time (Wursthorn *et al*., 2004).

There are three problems concerning ARS use in first responders' equipment:

- Development of AR devices for first responders. These devices must be light and safe and use a large capacity battery
- Development of GIS
- Development of a communication method that enables one to instruct first responders, to share knowledge among groups of experts.

3.1. MOBILE AUGMENTED REALITY SYSTEMS

Use of ARS for navigation purposes is allied with wearable computers technology. Intensive research in the field of wearable computers is conducted in the Wearable Computer Lab at the School of Computer and Information Science, University of South Australia within the framework of the Tinmith project (Tinmith, 2007) operated by Dr Wayne

Figure 5. Tinmith 2006 mobile AR system. (Images courtesy of Dr. Wayne Piekarski, University of South Australia.)

Piekarski. Tinmith outdoor AR system is a backpack system (Figure 5). Their current 2006 model includes a custom modified Pentium-M 2.0 GHz computer with Nvidia GeForce 6600 graphics. They use sub-50-cm accurate GPS receivers and an InterSense orientation sensor for position tracking. A helmet with a head-mounted display is an output device. The system contains two 8,000 mAh Ni-MH batteries for 3 hours of operation.

Research of mobile AR systems is also conducted in the Computer Graphics and User Interfaces Lab at Columbia University under the guidance of Dr. Steven Feiner (project MARS (Güven and Feiner, 2003)—Mobile Augmented Reality Systems). Quantum3D ExpeditionDI (Quantum3D, 2006) is a popular immersive training and mission rehearsal platform for dismounted infantry (DI) using mobile AR.

Progress of mobile ARS is obvious. Still, there are some problems to be solved to apply this technology to first responders' equipment:

- Tinmith system can operate for 3 hours without recharging. It is enough for the ARQuake game, but not for rescue operation. Small, light and effective accumulators should be applied (e.g. direct methanol fuel cell).

- An effective input device is essential. Gloves as a special input device for ARS might be suitable for building design, but not for rescue operation.
- Displays must be effective in all lighting conditions. Wearable computers must be light and easy-to-wear. User interface must be intuitive, which is of particular importance in an emergency (Leebman, 2004).

3.2. GEOGRAPHIC INFORMATION SYSTEMS

Application of geographic information systems to emergency management has become a popular research topic recently. Prof. Dr. Peter van Oosterom and Dr. Siyka Zlatanova (Delft University of Technology, the Netherlands) organize a special annual symposium on Geo-information for Disaster Management (Van Oosterom *et al.*, 2005). As mentioned above (see Section 3) ordinary two-dimensional (2D) digital maps are unsuitable for emergency management. It is much more convenient to orient oneself in "real" 3D space rather then to use a 2D map with obscure notations. Three-dimensional GIS needs a special interface to maximize its advantages.

Public Participation GIS (PPGIS) is a research field, which tries to adapt GIS to be used by ordinary people rather than GIS experts (Haklay and Tobon, 2002). PPGIS uses a usability engineering (UE) approach that focuses on interaction between a user and a computer, usability and effectiveness of an interface, error handling. In spite of their advantages, UE systems do not take into consideration limitations imposed on social and organizational aspects of collaboration of experts so they may be useless for teamwork.

Cognitive System Engineering (CSE) approach to interface design for 3D GIS is described by Brewer (2002). CSE focuses on the interface between an expert, whose task is to make decisions, and the structure of an application domain, and studies how this interface influences cognitive processes and collaboration. Non-GIS specialist users often cannot build a query to sophisticated 3D GIS software. By joining GIS and CSE together we can create a system to process natural language queries and to interpret gestures as control instructions. It could help both first responders and management personnel focus on their work, not on GIS interface.

3.3. VIRTUAL ENVIRONMENT IN EMERGENCY MANAGEMENT SUPPORT: INTEGRATED SOLUTIONS

When saying "integrated system for emergency management support" we mean a system that includes AR devices for first responders, provides communication between groups of experts and uses 3D GIS for navigation purposes. Actually, there are two separate lines of investtigation today:

- Mobile AR systems and communication technique
- GIS in emergency management.

These efforts if joined will lead to a superior emergency management support system. Now there are some prototypes of such systems. One of them is under development at the Universität Karlsruhe (Leebman, 2004). The solution is intended for earthquake response using AR technology. A method to establish the match between real-world scenery and a virtual extension is proposed. However, the system does not use GIS and does not provide communication between experts.

The project "Advancement of geoservices" (Wursthorn *et al*., 2004) aims at integrating GIS and AR technologies in rescue equipment. Four working groups develop web-based GIS components to provide online access to spatio-temporal objects, work on Augmented Reality GIS Client, do research on mobile data acquisition, usage and analysis and development of standardized interfaces for geoservices. An ARS application to flood disasters (Wursthorn *et al*., 2004) is a practical implementation of these methods.

An integrated system for both first responders and management personnel support is described by Zlatanova *et al*. (2007). It solves some of the problems concerning GIS application to emergency management and provides navigation for rescue workers, decision support for management personnel and communication between them. But VE technologies are used only in a control room. There are no AR systems for rescue workers.

An ARS application to flood disasters management (Thalmann *et al*., 2006) is another initiative. Data acquired with airborne cameras is superimposed on additional information, which forms MR. A Cave Automatic Virtual Environment (CAVE) system visualizes MR in a control room. Rescue workers use PDAs (Personal Digital Assistants) instead of mobile AR devices.

There is no full-scale integrated emergency management support system at the moment, but there are prerequisites for it and some prototypes.

3.4. DAMAGE EVALUATION AND RECONSTRUCTION OF BUILDINGS

An AR system can be a tool for inspectors, architects and constructors who work on a building site for damage evaluation and reconstruction of buildings during the recovery phase of an emergency. Inspectors evaluate damage visually and perform necessary measurements manually. This labor-consuming method can be improved by applying AR technology (Kamat and El-Tawil, 2005). The idea is to superimpose an actual image of a building after an accident on an virtual image of a building before damage occurred. Inspectors who are equipped with mobile AR systems "correct" a virtual building to match it with a real one. Then automatic analysis of the extent and amount of damage is performed.

Another field of AR application is so-called "X-Ray vision" (Bane and Höller, 2004). It enables one to see invisible objects (e.g., electrical communication lines or elements of the load-bearing structure of a building that are hidden behind walls (Webster *et al*., 1996)).

4. Control Room

Management personnel must be aware of a situation and have all relevant information to choose the best decision in an emergency (Beroggi *et al*., 2003). Video-surveillance can be impossible due to smoke and damages. Sometimes management personnel need additional information that is inaccessible to video-surveillance systems. Virtual environment system can be a suitable interface to represent all these information to management personnel.

4.1. USING GIS IN A CONTROL ROOM

We have already discussed GIS application to information systems for first responders (see Section 3.3). Geographic information systems are of great importance for a control room. Most of the information to be

analyzed in an emergency is spatially dependent. People have used paper maps to plan military and rescue operations for a long time and still prefer them to digital ones. Paper maps have not only been a method of geographic information representation, but a means of communication between experts. Researchers outline several problems concerning GIS application to emergency management (Cai *et al*., 2006).

Data have to be analyzed and visualized immediately in an emergency since a five-minute delay can make information irrelevant. The necessity for a mediator (GIS analyst) between GIS and experts degrades the quality and delays decision-making. In particular, the WTC tragedy revealed that interfaces of modern GIS do not enable experts to process information and make decisions in time (Cai *et al*., 2006). Experts have to crowd in front of a small monitor and discuss possible response strategies when using digital maps. A big screen itself is not a solution to the problem. The system must be interactive and enable non-GIS professionals to build a query.

A VE system together with a new kind of interface can solve the problem. Cognitive GIS developers propose such a new interface (Cai *et al*., 2006; Brewer, 2002). They use a combination of speech and gestures as a query language. Implementation of this system involves the difficulties in natural language processing in general and spatial queries processing in particular.

5. Conclusion

We have reviewed opportunities that visualization and VE technologies offer as applied to emergency management during both the preparedness phase with the aim to avoid an incident and the response phase to forecast development of an emergency, choose the best response strategy, rescue people, evaluate damage and reconstruct buildings. We have considered the following groups of potential users of the system: researchers who simulate possible emergency circumstances, experts who choose between different response strategies and first responders, constructors and architects who work on a site.

Each of the topics in this review is quite extensive and merits further consideration. To sum up, there is no full-scale integrated emergency management support system at the moment, but there are prerequisites

for it and some prototypes (Wursthorn *et al*., 2004; Leebman, 2004; Thalmann *et al*., 2006).

There is a growing interest in application of new technologies (VE, in particular) to emergency management. Recent advances in this area come from noticeable progress in wearable computers technology and reduction in the size of these devices. Nevertheless, careful research should be conducted and an integrated solution should be developed before VE systems will find their practical application to emergency management. We believe that this challenging problem will be solved in the near future and the solution will come to the aid of people in emergency.

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THE ROLE OF SIMULATION EXERCISES IN THE ASSESSMENT OF ROBUSTNESS AND RESILIENCE OF PRIVATE OR PUBLIC ORGANIZATIONS

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Abstract: This paper deals with the organization of simulation exercises to prepare organizations to face emergencies. The original objective of such simulations is to train people to emergency procedures and devices; we raise the question of training people to face potential crisis situations: are simulations fitted to that objective? Through the observation of a number of exercises organized by private companies and rescue services, we can answer that naïve interprettation of simulation results limits their benefits to the correction of gaps between rescribed and observed actions, without addressing complex organizational behaviour. We introduce a method to organize simulations that gives access to this complexity and to the resilience and robustness apacities of the organization by giving specific roles to observers. This method uses a model of the organization seen as a combination of three levels: structures, relations and meaning.

Keywords: emergency management; simulation of accidents; organizational learning; resilience; robustness

1. Introduction

With the growing complexity of technological and organizational systems, companies and public bodies have developed the use of

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simulations, exercises and drills in order to train their staff to face hazardous situations.

These simulations are related to emergency plans: dangerous situations or critical phenomena that have been identified as potential threats are played out and analyzed with the aim to define or check prevention and protection measures and to validate intervention plans. Exercise scenarios are designed to give people opportunities to "play the game" in realistic conditions, practice plans and test the use of technological devices.

Our observations and analysis of a series of simulations (toxic leak in a refinery, fire and toxic gas in road tunnels, terrorist attack in the metro, etc.) have shown the benefits but also the limitations of such simulations in terms of lessons (behaviors, decision making) learned by participants.

Among the benefits, the setting up of the exercise is in itself a good opportunity to gather the many stakeholders and to discuss "who is in charge of what"; this facilitates mutual knowledge among technical staff and shared values in the different organizations. The second kind of benefit is the test in realistic conditions of the technological devices and means (medical tents, fire extinction means, communications, etc.) and their use.

Among the limitations, the poor level of realism of the simulation is often an obstacle to the commitment of participants, who don't react as they would in a real, stressful situation. Another limitation lies in the evaluation method; people are evaluated for their strict application of plans, compared to "official" plans and procedures. Any difference in behavior is seen as a violation of rules and sanctioned or at least pointed to as an error, which strongly reduces people's willingness to innovate.

From this analysis, it can be concluded that simulations are efficient in creating opportunities for people to work together and to improve their practice of anticipated situations. But do simulations improve the ability of organizations to avoid or manage crises? Based on different non-participant observations and in-depth interviews, our answer is "no," to the extent that their analysis is limited to the identification and correction of deviations from the prescribed tasks.

We define a crisis as a situation in which an organization is overwhelmed and destabilized, as compared with emergency management, a situation in which the organization remains in control, applying

known plans and procedures (Wybo, 2004). In this context, resilience corresponds to the ability of the organization (at any level) to keep achieving its tasks by adapting its functioning to hazardous situations, uncertainty, time pressure and threats. Robustness corres-ponds to the ability of the organization to survive and stay under control by the emergence of new organizational patterns.

In observing simulations, we have identified individual and collective reactions to difficulties that were neither part of the scenario nor foreseen in the emergency plans. If the difficulties are relatively small, individuals and groups use their skills and experience to adapt plans, procedures and behaviors, in order to achieve their tasks in those degraded contexts. By doing so, they contribute to the organization's capacities of resilience. When faced with unanticipated and threatening events or situations, some people (generally the most experienced) show capacities of robustness: they emerge from the group, commit themselves to "do something" and find innovations to cope with the real situation. In some of those situations, new organizational patterns emerge, for example the creation of different communication flows or an alternate distribution of tasks. With such actions, those individuals and groups demonstrate their capacity to contribute to a higher level of robustness in the organization.

In order to go further in this reflection, we have designed a method to observe and analyze simulation exercises, allowing the identification of such behaviors, the context in which they appear and the lessons that can be learned from this analysis in terms of resilience and robustness capacities (Wybo *et al.*, 2006).

2. The Role of Simulations

2.1. EMERGENCY MANAGEMENT AND RISK PERCEPTION

It is now widely accepted that safety management inside the organization has to consider, in addition to the physical characteristics of dangers in the working place, the way risks are perceived by those involved.

The study of risk perception inside organizations deals with the comprehension of tasks and the definition of working situations when these may constitute a threat for the physical integrity of personnel,

installations security, and even the safety and health of populations outside the organization.

Taking risk perception into account can be considered as one remedy for "normal accidents" as suggested by Weick (1986) who shows that systems vulnerable to normal accidents (Perrow, 1984) are at the same time contexts where individuals try to understand and manage complexity. Weick suggests preventive and learning actions through which individuals and groups become able to build elaborated interpretations of what they do and experience, leading them to analyze events other than those strictly limited to technical matters. Jacques *et al*. (1999) have shown, using cognitive mapping, the evolution of learning over time by using preventive learning technique.

The challenge is thus for the organization to integrate safety management in two manners: first by taking into account human and organizational factors and not only technical factors of safety, and second, through involving fully all the actors inside the organization. When the risk of accident concerns outside populations, a wide array of stakeholders can be involved.

Safety integration can be achieved through training and preventive actions. A second way is through simulation. The specific advantage of simulation as a source of lessons is that it puts forward many aspects of what people prefer not to think about in their everyday working life situation: accidents and crises. In terms of perception, a simulated accident makes manifest events which otherwise might remain unknown, unseen and unheard of.

The simulation of a large accident involves many different players whose role is to intervene in case of accident. In normal times, these people do not meet nor are part of the high reliability organization (they are generally not part of the organization in charge of the routine activeties). When the accident occurs, they must understand the situation, switch from the routine work to emergency management, co-operate and coordinate themselves in order to mitigate the accident and keep the situation under control. This very fact is in itself a complex organizational achievement, costly in terms of material and human resource mobilization.

Under normal operations, it is the occurrence of the accident that triggers a wide array of events, ranging from the focus of attention of personnel to the calling together of many outside players. The accident has the upper hand. In the case of simulation, the human minds of

scenarists will take the lead. What difference does this make? This is what we aim to distinguish here, principally in terms of learning, which is chief among the assessment of resilience and robustness capacities of organizations.

Put simply, one can say that simulation creates for the organization an intermediate state between normal operations and crisis situations. While some of the preparedness required to face potential crisis situations can be acquired during normal times, other levels of learning can be acquired only outside normal situations, i.e. during crisis situations or simulations.

We focus in this paper on learning during simulation situations. To understand the dynamics of this type of learning, we have to consider some aspects of safety management in ordinary times. How safety is recovered during and after a crisis can then be examined on that basis.

2.2. SAFETY MANAGEMENT IN NORMAL TIMES AND DURING CRISIS

When a safety issue is raised, one may observe that everyone in the organization has an opinion on the question. While the starting point of this opinion is the shared objective to avoid accidents and prevent operational errors, reasoning and references, often implicit, may rapidly diverge.

This can occur according to the position and role of the actor, his knowledge of risks and operations, possible defensive mechanisms that are in use in his working environment (Argyris and Schön, 1996), (Dejours, 2000), orientations set by the hierarchy and the top management, etc.

In addition, the perceived contradiction between the *a priori* shared goal of a high level of safety and secondary divergences can lead to misunderstandings or stalled situations, which in turn are counterproductive for safety. The extent and efficiency of preventive actions, as well as communication with stakeholders, can thus suffer.

Organizations are bound by many levels of requirement or obligetion in regard to safety assurance (Poumadère and Mugnai, 2006). The first level is individual obligation, which includes to follow consigns and basic rules, such as wearing the mandatory individual protections. Obedience is a must, along with the notion of self protection and, in some cases, that of survival. In most settings and most of the time, this

level of obligation can appear disconnected from the apparent requirements of tasks. However, during accident and crisis situations, this basic level plays its full role and it is expected to be automatically integrated in behaviors. This context may restrain individuals to commit themselves to adapt procedures or innovate, as this behavior will be perceived as violations of rules.

Another level is that of economic obligation; simple economic rationality favors investments in prevention so as to avoid the very high direct and indirect costs of accidents. This level is most often disregarded during accident and crisis, as urgency prevails and exceptional expenditures may be undertaken. Even so, adaptations and innovations achieved on the spot are often done with very few resources, but without a clear evaluation of costs that may result later on from these actions (either in reduction or aggravation of damage).

The managerial obligation resides in the fact that safety figures among collective performance factors and must be managed to that effect, in itself and alongside other performance factors with which it is in interaction. During accidents or crisis, this managerial coordination of decisions is likely to be crucial, as long as the system remains under control of the organization. When the situation goes beyond the limits of routine, this obligation becomes less and less crucial compared to the willingness of players to do something useful at their own scale. In resilient organizations, the management will decentralize control and give to their staff more and more degrees of freedom in action as the situation escapes from control.

The legal obligation refers to the existence of the organization within a state of law, applied to all organizations which have to conform to established norms and prescriptions. Often this level prevails in the organization when safety is considered; i.e., safety actions and investments may be framed as responses to minimum legal requirements. However, during accident and crisis situations, the need to invent ad-hoc solutions and organizational patterns may make that level less predominant. In a similar way than individual obligetion, legal obligation reduces the willingness for adaptation and innovation, as people may be sanctioned for violating rules, especially if there are casualties and financial damage.

The professional level of obligation corresponds to the best possible application of scientific and technical knowledge by Safety experts; in some contexts all members of the organization are invited

to integrate safety within their professional identity. During degraded situations, experts tend to consider adaptations and innovations as a "normal way" to use their skills and experience when they have to cope with a risky situation. By doing so, they will be reluctant to talk about (either because they think that every professional would have done the same or because they want to keep secret what gives them the status of expert) and this "expertise in action" will not be shared and learned by other players.

The reciprocity obligation corresponds to interdependency and solidarity, which exist *de facto* within working relationships and make each of us responsible for others' safety, which can extend to relations with the environment of the organization and its protection. This obligation plays its role during degraded and crisis situations and contribute to organizational resilience as it governs interactions among players.

The moral obligation puts forward the value of human life, primordial within our cultural ethics, and for which better safety for all is a goal. This obligation plays an important role in the commitment of people when they perceive threats for other people.

These levels of obligation influence perceptions and role playing at all levels of the organization and thereby influence safety practices in routine activities and during emergencies. As shown above, obligations change in meaning and salience according to whether the organization is in a normal, degraded or crisis situation. It is thus useful in each context to assess safety obligation levels, both in ordinary times and for accident or crisis situations. The bridges built between these two different instants in organizational life can contribute to resilience and robustness if it is possible to observe and analyze them. This is our main objective during the simulation exercises.

2.3. INTERPRETATIONS OF SIMULATIONS' ANALYSIS

In the usual way of organizing exercises, one uses a rational model to measure the gaps between prescribed and observed actions as the scenario unfolds, and to explain in an objective way the causes of those deviations. This approach can be called "naïve", as it doesn't reach the complexity of the organization during emergencies and crisis. It can be associated with "simple-loop learning": measuring gaps and correcting them.

In this paper, we present a method to observe an organization during a simulation based on the plurality of specialized observers' points of view. Taking their observations together allows us to address the complexity of organizational behavior, to generate meaning and learning from the post-simulation analysis and thereby to go beyond the simple diagnosis of deviations from standard practice. The method is framed by a three dimensional model of organization: structures, relations and meaning:

> that of structures in which actors' games take place, that of relations between actors who set structures in motion, changing them through their games, giving rise to new organisational forms. This dimension also takes into account the principles of (sense making) legitimacy through which actors justify their games and their constructed orders (Jacques and Specht, 2006).

2.3.1. *Structures*

Structures consist in what is prescribed by the organization, objectivable and measurable: the product of division of work, tasks, the means to achieve tasks, formal rules, procedures, technology, coordination tools and artifacts, etc.; what Mintzberg (1993) calls the hierarchy line, techno-structure and support services. This first layer allows the organization to deal with its routine tasks in a safe way: the "normal situation" is under control. It is associated with hierarchy: control is achieved by the management layer.

2.3.2. *Relations*

Relations are often represented as the roles played by the different actors. Following Crozier and Friedberg (1977), this dimension takes into account the fact that the structure is a context for action, which includes relations and interactions among people.

Each actor provides his resources, stakes, interests and power. This dimension can be observed at the micro/local level. It concerns verbal and non verbal, formal and non formal communication. It raises questions about the group's dynamics. This second layer gives the organization its flexibility to deal with deviations. By interacting, people adjust their activities to cope with changes from the routine conditions in order to proceed with their missions and put the system back into its normal state. This layer corresponds to the resilience of

the organization. It is associated with networking: control is achieved by a series of adjustments and interactions at different levels of the hierarchy.

2.3.3. *Sense*

Sense making is what people use to justify their actions; it is related to the notions of legitimacy, ethics, interests and values. The actor's representation of the situation influences his behavior. People belonging to different "worlds" have difficulties to act together for a common task (Boltansky and Thévenot, 1991; Weick, 1992).

Organizations that are able to make sense of ambiguous and uncertain situations demonstrate their plasticity to deal with unforeseen situations, pressure of events and uncertainty, and to avoid chaos and crises. This layer corresponds to the robustness of the organization. It is associated to emergence: control is achieved by people at any hierarchical level that invent ad-hoc solutions where and when they are needed to ensure the survival of the organization.

3. Organization of Simulation Exercises

In order to be prepared for emergency management activities, risk-prone companies and rescue services organize on a regular basis exercises that simulate accidents and catastrophes. In France, for instance, a national regulation requests that all dangerous industrial sites organize once a year a large exercise with rescue services and local authorities.

The purpose of such exercises is to train people to apply procedures and plans, to become familiar with technical systems and locations, and to evaluate the efficiency and appropriateness of procedures. Their objective is also to give opportunities to the different organizations to communicate and act together. These practical sessions have one more advantage: they can be organized more frequently than staff turns over.

In this way, teams become accustomed to work together and if some need for improvement is identified, progress can be assessed during the next exercise, as it will be carried out by the same people in comparable conditions. This advantage is especially great when the exercise concerns very rare events and/or when the stakeholders have a

high rate of turn-over. By running exercises at an appropriate frequency, the organization increases its capacities to face “known events.”

3.1. PREVENTION OF CRISIS: THE ROLE OF SIMULATIONS

When dealing with the management of crisis situations, the interest of such exercises in terms of training can be questioned. Crises are situations in which plans and procedures are not appropriate, so how exercises can provide experience for such situations? How may exercises increase the resilience and robustness of organizations?

By placing observers in appropriate locations with precise missions during emergency exercises, we observed that people playing their roles in the exercise sometimes go beyond the procedures describing their tasks: when facing various types of difficulties (included or not in the scenario), they develop communication and coordination activities with other people (inside and outside their organization) and they adapt their activity to the real context in which they are. If the debriefing of the exercise is focused on the strict application of plans and procedures, such deviations and ad-hoc solutions are evaluated negatively by the management and so, they are generally hidden or minimized by the participants.

> Given the emphasis on plans, even those that are impossible to execute, it is not surprising that departing from them is often cited as evidence of a failure. Disasters, however, break the rules that guide the ordinary conduct of business and government, at least for a period of time. Disasters create new environments that must be explored, assessed, and comprehended, change the physical and social landscape, and therefore require a period of exploration, learning, and the development of new approaches (Kendra and Wachtendorf, 2003).

These deviations from the standard procedures are indicators of the ability of people to adapt to difficulties and by that, they reveal on one hand the need for adaptation of procedures and on the other hand the resilience and robustness capacities of the organization: the ability of people and groups to be flexible and innovative to avoid destabilization and crises.

3.2. ANALYSIS OF EXERCISES

Simulating accident situations and collecting lessons learned is a challenge both for authorities and for other stakeholders involved. Accident is a sensitive situation including technical malfunctions, human errors and organizational flaws as root causes. Accident investigation in general is often closely focused on finding causes of the accident and less effort is put in studying organizational factors that influence the effectiveness of emergency management.

Beyond these difficulties, exercises provide an important source of information about emergency management in accident situations. The major advantage of simulated cases is that it is easier to collect lessons learned and to identify difficulties, if precautions are taken not to put too much pressure on participants about responsibility. Tackling the question of guilt can form an obstacle to the collection of relevant information about errors and organizational drawbacks from participants.

Analysis of simulation exercises is based on a method which main objective is to develop organizational learning from accidents and crisis. This method was originally designed for the analysis of real accident situations in industrial plants, public transport (Wybo et al. 2002), floods and oil spills.

The method associates people who have been acting at different levels of hierarchy and in different organisms along the development of the situation. It is based on collecting individual stories from those who have been involved in the management of an accident situation and sharing these individual experiences among them in order to develop an organizational learning process.

In the case of real accidents, we select representative people that participated in the management of the accident at different levels of the hierarchy and from the different organizations (company, rescue services, officials, etc.).

In the case of simulation exercises, we introduce two categories of people in the process: a set of people that played the simulation and the group of observers. By this way, we get a chance to access the insights of the organization at work during the exercise and to identify aspects concerning the three levels: structure, interaction and sense.

Each interview starts with the interviewee telling his “own story”. From that narration, the researcher points out the key moments in the

story and asks questions like “why did you do that?”, “how did you do that?”, “what else could have been done?”. By this way, relevant information about explicit knowledge (context, events, actions and decisions) can be identified from the story, along with some tacit knowledge: perceptions, motivations and alternatives. (Wybo, 1998).

This knowledge is formalized as a set of “particles of experience”. These particles of experience constitute the meaningful pieces of memories of each person having experienced a stressful situation. They represent either the person’s reaction to an event or his actions to cope with a change in the current situation. An overall picture of the development of the situation is then drawn by the researchers, by merging information from individual stories into a collective story. Each particle of experience is divided into four phases:

- Context: the main aspects of the current situation
- Analysis: how people perceived (on the spot) the situation and its evolution, and the hypothesis that were considered
- Action: decisions made and actions carried out
- Effect: a posteriori evaluation of effects of actions on the development of the situation.

This common story is then discussed and validated during a “mirror meeting” gathering all participants, in order to reach an agreement among them and to identify lessons to learn from the management of that exercise.

The collective processing of individual perceptions, suggestions and experiences favors the commitment of participants to the conclusions reached during the process, which is very useful to promote learning in the organization and to apply the lessons learned in the future.

3.3. OBSERVATION OF EXERCISES

Based on this method, the introduction of specialized observers was tested in several exercises, in order to get the full picture of the organization at work and to identify these deviations from the prescribed world, from the combination of the points of view of the participants and the points of view of the different observers.

Three kinds of observers were defined: those who observe the activity of key people (information they receive and emit, people with

whom they collaborate, decisions they make, etc.), those who observe a specific task (how it is achieved, difficulties encountered, who participates, what resources are used, etc.) and those who observe a specific place (who is there, what is done, how this place is perceived by people, etc.).

Using this combination of points of view (people playing roles and specialized observers), we build the "full picture" of the simulation that we present to the players during the debriefing session. This analysis results in the identification of a number of deviations, in particular the emergence of organizational patterns and communication flows among stakeholders, some of them proving efficient to prevent the situation from turning into crisis. Studying the character and value of these deviations makes it possible to capitalize on them to improve emergency procedures and plans, and to increase the mutual knowledge and efficient cooperation of stakeholders (Wybo, 2006).

> The reliability of learning of an organization is if it develops common understandings of its experience and makes its interpretation public, stable and shared (March *et al*., 1991).

3.3.1. *Case 1: Assessment of Resilience Capacities*

We present here an example of this method to the simulation of an emergency in a road tunnel. The scenario was: a truck carrying a toxic gas tank stops in the tunnel as its tank is leaking; the driver goes to the nearest emergency shelter and calls the tunnel control room; four cars and a bus are in the tunnel at that time and stop at a walking distance from the truck.

This exercise was set to test the management of such accident and to understand the behavior of passengers before the rescue services reach the site. More than 200 rescue people participated in the exercise, plus passengers of vehicles, tunnel operators, policemen and officials in the control room. 30 observers participated in the instrumentation of the exercise.

During the exercise, the tunnel management software partially failed (this was not in the scenario) and it was no more possible for the operator to answer calls from rescue shelters in the tunnel with the usual hardware (PC display, mouse and audio helmet). He remembered that there was a secondary rack that permitted to answer those calls, but this rack was difficult to access (in a dark part of the room,

near the ground) and the indication of the calling shelter number was difficult to read (small digits, not illuminated). Anyway, the operator took with him a paper map of the tunnel with indication of shelter phone numbers and locations and began to answer calls.

By the way, he succeeded to get essential information from the people calling, reassure them and give them simple indications to be safe while rescue forces were on their way. This is an example of the robustness capacities of this operator, which allowed him to keep people safe in the tunnel and to give precious indications to rescue services (how many people, in which locations: cars, bus and shelters).

3.3.2. *Case 2: Assessment of a lack of robustness*

On the other side, it is also possible to observe and understand some drawbacks that would ruin the efficiency of emergency management in a real situation.

In the simulation of another accident in a road tunnel, two observers were placed in the control room of the tunnel: one observing the manager on duty and the other observing the activity in the control room. At the same time, other observers were inside and outside the tunnel (15 observers participated in this simulation). When the simulated accident occurred (collision of a car with a truck, putting fire to both vehicles), some of the car passengers, shocked but not wounded, were wandering on foot in the tunnel, looking for an escape route, and the rescue services took a long time to localize and shelter them. In real conditions, those people would probably die from smoke heat and toxicity.

By combining observers' data, we identified the organizational cause of this difficulty. The control room operator was facing a set of video screens in which it was possible to observe these people wandering in the tunnel. At the same time, in a corner of the room, an operator from the rescue team had established a radio terminal to communicate with their colleagues in the tunnel and they were listening to the conversations over the radio. Finally, the manager on duty was trying to assess the situation and prepared to answer the requests that he could receive from the chief of rescue forces (located at one of the exits of the tunnel) or other stakeholders.

But the operator had not been told to report to the manager what he saw on the videos (he was trained to answer questions, not to be proactive) and the operator managing the radio terminal was not

trained to identify problems that his colleagues encountered in their actions from what he heard over the radio, so none of them communicated to each other or to the tunnel manager.

When the analysis of the different observations (in the control room, in the tunnel, at the rescue headquarters, etc.) was carried out, this drawback appeared as a lack of capacities of sense making in this group of people: none of them took an initiative to invent a form of cooperation that was not defined in the emergency plan.

From this analysis, it was possible for the tunnel managers and the rescue officers to share these results with their staff and to set up improved emergency procedures. This analysis also pointed out the importance of interactions among people from different organisms and proactive behaviors to build resilience and robustness capacities; otherwise even the best structure (cameras and video screens, wireless communications, procedures, etc.) is useless in such degraded situations.

4. Conclusion

Simulations are one of the most efficient tools that can be used to train people to emergency situations, especially for situations with a low frequency of occurrence and a high potential of damage.

Emergency services and risk-prone companies have gained significant experience in the setting up of exercises and this practice contributes to the capacity of their organizations to face “planned” emergencies (reinforcement of the structure layer).

In order to face situations that may turn into crisis, because of surprise, speed of development, uncertainty, lack of resources or difficulties in communications among stakeholders, organizations need to assess and develop their resilience and robustness capacities. In this paper we have shown that exercises can contribute to that on the condition that their analysis goes beyond naïve interpretations and gives access to the complexity of organizational behavior, specially the levels of interaction and sense making.

The method presented here provides means to reach this objective with only minor changes in the simulation set up. By defining specific missions for observers based on a model of organizational behavior, it

is possible to identify more precisely the organization's resilience and robustness capacities and handicaps.

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CONCLUSIONS WITH RESPECT TO RESEARCH DEMANDS

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1. Introduction

Near the end of the workshop the experts clustered in three groups and collected in a round-table discussion subjects which would be fruitful to do research work on to enable progress in increasing the resilience of urban structures. In addition a fourth team contributed on a new technical subject namely the monitoring of structures.

First, questions concerning threat analysis will be posed, then how to motivate and educate people will be discussed and what resilience principles can be distinguished. Subsequently materials and structures are considered and finally the possibility of monitoring of structures. More research questions are of course mentioned in the foregoing Chapters, while at the end a brief summary will be presented.

2. Group: Threats and Consequences, leader F. van het Veld

The aim of sabotage or terrorist attack is not only to create the greatest possible damage, but also to destabilize normal life. The following items were considered:

- Identification of threats (and scenarios)
- Identification of the consequences

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- Development of protection systems to prevent and mitigate the consequences
- Emergency plans to manage crisis.

General research questions concern in the first place the scenarios which reflect the current threat:

- Identification, definition
- Consequences and frequencies
- Mitigation/crisis management.

To link resources (e.g. funds) to solutions e.g. in the form of countermeasures or mitigation, one needs methodologies to prioritize. Which methods/parameters can be applied to that end? Consequence models, scenario analysis, probabilistic approaches, cost/benefit analyses, QRA—quantitative risk analysis? More specifically research is recommended on the following points:

- Characterization and modeling of natural and technological (terroristic) hazards as a robust scientific base for spatial planning and licensing. This comprises a large variety of threat descriptions and models of dispersion of toxic and biological agents, evolution of fire in structures, impact and explosions. Basic models exist, but inaccuracies and uncertainties are relatively large.
- Emerging technologies: what are the (new) threats? What don't we know? Usually this is the most difficult question to solve.
- How do we protect our basic/natural resources (water, energy) and basic societal services (e.g. hospital, communications, transport) against attacks?
- How much and which information should we share? What is the best balance between open and restricted information? How to cope with this dilemma? What's on the Internet?
- Sharing information between intelligence community and scientists is recommended to increase the quality of the threat prediction, e.g. with respect to a better estimation of the probability of an event.
- Further research shall be undertaken on how to mitigate consequences and how to prioritize consequences in view of planning for it.

- Soci(et)al preparedness: How do we plan ahead?
- Multidisciplinary approach on e.g. media/politics influence on intensity and/or perception of terroristic threat/consequences. What are the psychological effects?
- Design of consequence reducing measures to increase resilience.
- Can organized crime be defined as terrorism, e.g. from a financial point of view?

3. Group: Organization for Preparedness and Emergency Response, leader Prof. J.-L Wybo

Status and key dimensions of the problems were discussed. A number of issues was identified.

In the first place human beings should be placed in the center. Educating the people is first priority. This means education of emergency responders, education of the population (schools,…), but this shall take into account the risk perception of people. Objectives of education are: Recognizing the risk, learning to trust organizations, and learning which action to take (What to do?). A question that comes to the mind is: Who should do the training?

Perceived risk can motivate. People are more willing to change their behaviour if they have the feeling of "being at war" (example of Israel). There is also the Japanese example, where individual and group behaviour seems to be quite appropriate in case of disaster.

Stakeholders (politicians, administrations, experts) shall network and cooperate. Another important aspect is a clear level of alertness. There should be clear information about what risk/threat there is and about knowing what to do until the arrival of rescuers. Learning from past experiences is essential. For that purpose data should be collected and cases analyzed.

Resilience principles in different disciplines shall be integrated. Resilience principles for the (spatial) planning process are transparency of decision-making, good communication and a good negotiation process between politicians/administration and the public, trust building in institutions and a clear definition of roles with a sense of responsibility of actors.

New challenges are how to deal with new risks and in particular with “unknown” risks? New ways of organizing mass evacuation shall be designed e.g. by promoting “autonomous units” in populated areas (principle of autonomy).

A number of challenges and research questions have been formulated: Primary question is urban resilience—Utopia? (Ideal resilience vs. challenges of practical implementation). What is our idea of a resilient city? A second point is how to introduce resilience principles into different disciplines? How can priorities be defined to allocate resources most efficiently in order to create more resilient cities? In connecion with this is the question how to produce a reliable information basis for decision-making and how to design co-operation between investors, people, and authorities. Since it will involve costs, we also have to find a way to institutionalize the implementation of building standards. Finally: How can people be motivated and involved?

When considering the problems we shall be aware that urban structure consists of a physical/environmental structure, a socio-economic structure, and an institutional structure.

Key resilience principles to be distinguished are:

- **Redundancy and loose coupling:** Systems designed with multiple nodes to ensure that failure of one component does not cause the entire system to fail
- **Diversity:** Multiple components or nodes versus a central node, to protect against a site-specific threat and common-mode failures
- **Efficiency:** Positive ratio of energy supplied to energy delivered by a dynamic system
- **Autonomy:** Capability to operate independently of external control
- **Strength:** Power to resist a hazard force or attack
- **Interdependence:** Integrated system components to support each other
- **Adaptability:** Capacity to learn from experience and the flexibility to change
- **Collaboration:** Multiple opportunities and incentives for broad stakeholder participation.

4. Group: Materials and Structures, Leader Prof. V. Kodur

First of all design parameters against extreme load have to be defined. This holds for wind loading, e.g. hurricane, for earthquake, although normally considered in seismic design, but also for differential soil movement including erosion. It further holds for explosive blast, including internal explosion, impact of various kind, fire, extreme snow storm (beyond normal design conditions) and some combined loading. Materials to be considered are concrete, steel, wood, masonry, composite, including plastic, glass and gypsum.

The design approach consists of a structural layout (configuration). Structural analytical methods applied are linear elastic design for normal loading conditions, plastic design, and non-linear design needed for extreme static and dynamic loading conditions. Safety factors are well established for normal loading conditions. However in non-linear designs, the safety factors and failure limit state need to be discussed.

Next step is to define performance goals. These are:

1. Safety of the people
2. Preservation of the properties, mitigation of damages
3. Restoration, reparability, stability
4. Remote real time structural monitoring.

A strategy to achieve these goals is to prevent immediate term and short term progressive or localised collapse (points 1-3 above). This can be realised by redundancy to allow load distribution, by installing protected zones (1) through safe refuge areas and evacuation routes, by fail safe design (1) and minimising structural damage (1-3).

A series of knowledge gaps and research needs were identified: So is for wind loading a testing procedure required and for earthquake resistant design a data base is needed. This holds too for differential soil movement. Explosive loading is well understood, this is true too for impact loading although a translation is needed from scientific to engineering level. For fire, extreme snow storm and combined loading more R&D is required. Material specifications up to failure conditions are needed under thermal, dynamic and long-term effects. Properties of new materials shall be determined and in particular their fire resistance and characterisation for combined loading be established. This may require improved test methods.

As regards structural layout zoning (leading to isolation of damage) is possible, if loading and structural behavior is well understood. Not clear is whether performance based structural design is possible. Beside the structural analytical methods mentioned above additional tools are necessary for combined load effects, to quantify loading, for fire resistant design, to determine an all failure limit state. All these tools shall be validated.

Safety factors are well established for normal loading conditions. However in extreme loading and non-linear designs, the load combination factors and the failure limit state need to be discussed.

Performance criteria of infrastructure shall be analyzed and assessed taking into account historical records. In this context there exists a need to retrofit, to retrofit materials, to apply strengthening techniques and performance monitoring.

In conclusion the following demands can be identified:

- Roles of material and structure are critical for urban resilience under extreme conditions
- Characterization and standardization of extreme load and load combinations
- Characterization of material properties under extreme environment up to failure limit state
- New materials for extreme environment
- Validation of design aids and approaches
- Improvement and advancement of assessment tools and retrofitting strategies for existing structures
- New codes and standards for implementing research into practice for achieving urban resilience under extreme loads.

5. Team: Monitoring and measurements of structural resilience, Profs. A. de Stefano and O.B. Vitrik

Modern civil engineering encounters various challenges concerned with multi-hazards causing highly intensive loading of urban buildings and structures, often complicated by harsh environmental conditions, chemically active media, fires, threats of terrorist attacks, etc. Therefore special and often contradictory requirements to building design

and materials are continually emerging. Accordingly the following tasks are becoming of increasing importance and interest to scientists and engineers working in civil engineering, structural health monitoring, and measuring system design:

- Monitoring of resilience, durability, and integrity of various urban buildings and structures, including frames, shells and foundations, bridges, and retaining wall, high-rise building, basic structures, etc. which demand measurement of strain, stresses, deformations, temperature, pressure, and other values characterizing destruction processes of materials in many points of structural components.
- Development of measuring systems providing correlation data between construction deformation and possible defects, both initial, and appearing during manufacturing and further exploitation.
- Development of security measuring systems for discovering of illegal penetration into potentially dangerous objects and locating a trespasser on the area under monitoring.
- Development of communication and processing systems capable to collect information from many sensing points, to store, and assess data, and to make their interpretation.

The main goal may be interpreted as to create some intellectual or smart or "intellectual" structure (building, bridge, dams, or number of such objects) similar to living creatures with ramified "nervous system" and "brain", and capable of telling where and what is wrong with its body.

The "brain", a computer with appropriate software, has to analyze the received data to provide damage identification and localization, hazard evaluation, and remaining resilience forecast. Parallel with standard methods it seems promising to concentrate on new approaches using fuzzy logic.

Another aspect is the availability of a knowledge base necessary to validate functioning of the "brain". Although past attempts have failed, it shall be tried to build a real maintenance knowledge base through the following:

- Get an overview of the state of the art of maintenance data-bases, including information recording formats.
- Propose a standard data recording form for each structural type or class with the highest possible compatibility with main existing

forms worldwide, making it possible to integrate the form with photos and experimental records.

- Study a data management system able to collect information and to make data-bases accessible in an open way.

Next problem is the “nerve system”. What element base and basic operation principles are most promising for such system? Last few decades demonstrated impressive progress in large-scale application of automated monitoring technology, development of various sensors both capable of integration in complex measuring systems and providing reliable real time information on the physical fields, objects, and processes under monitoring. Modern measurement techniques make wide use of optical, electrical, magnetic, piezoelectric and other types of sensors for Structural Health Monitoring. Significant progress of optical fiber communication lines technology resulted in the emergence of a new metrology field—optical fiber sensors, particularly fiber Bragg grating sensor, the application of which has im-presssively expanded in the last years. Another promising technology Micro-Electro-Mechanical Systems—MEMS—also demonstrated new possibilities for sensor production and application. Each class of approaches demonstrates it specific advantages and disadvantages. Therefore, it is important to discuss which sensor class or classes now seem to be most promising as a basis for physically and commercially successful strucural nerve system. The main criteria may be

- Ability to collect information sufficient to estimate the resilience, durability, and integrity of various urban buildings
- Ability of sensors to be embedded into material or produce a natural composition with structural components
- Durability, reliability and longevity
- Adaptability, self-verification and self-correction abilities
- Ability to be integrated into a unified monitoring system
- Cost of fabrication and installation.

A different important aspect is sensor networking and ramified structural “nerve system” principles. This has to include development of topology and architecture of networks including distributed sensing technologies, wireless, remote and other advanced approaches to the

collection of information from sensor network or areas under monitoring. Network robustness must be one of the priorities: sensor networks should be designed to be able to work even after loss of parts of the sensors. They need independent local power supply. Another challenge of distributed sensing is hardware integration: sensors for security and structural safety are different, but hardware integration can be an attractive way to convince the administrators of buildings and infrastructures to build "intelligent" objects. The same local and central data acquisition and management systems can support both classes of sensors.

Software integration is another topic: to handle distributed sensing it is necessary to involve ICT experts to include and assess algorithms for data reduction, data mining, data fusion, network robustness (to correct errors of single or multiple sensors). If the structural system under control is too complex to be represented by some kind of deterministic model, multi-variate stochastic symptom based monitoring approaches should be efficiently developed and assessed. Virtual reality integration into monitoring procedures could help operators even non-specialist to manage the monitoring results, alarms and warnings.

Global integration: Sensors measuring phenomena of different physical nature shall be integrated in the same system; it requires, of course, model and software able to handle heterogeneous information. Construction or coating materials can become sensing thanks to added micro- or nano-particles or fibers. In that case the obtainable information is scalar and a model to interpret the signal is needed.

Subsequently it seems important to research possibilities for enabling structural health monitoring by application of existing branched monitoring and communication systems including remote security systems, cell- phone networks and global satellite positioning systems. In this respect it is necessary to concentrate on the use of photo images in combination with micro cameras as auxiliary tools. These are available at low cost due to the massive production for cellular phones and can be associated to image processing software for some special applications e.g.: to follow the evolution of crack systems, or perhaps to replace electrical measures to detect corrosion. Also research shall be instigated to use optical systems to measure material degradation. Finally ground based GPS networks shall be developed.

6. Summary of recommendations

The Workshop's objectives have largely been met. Many aspects have been presented and discussed.

- *Threats & Consequences*: Studies have to be undertaken to identify the threats quantitatively and to determine what possible conesquences these can cause. Development of scenarios is required to prioritize measures and to link resources to possible solutions. Therefore research is needed to characterize and model natural and technological (terroristic) hazards as a robust scientific base for spatial planning. Potential new threats have to be examined. How can basic, natural resources such as water and energy and basic societal services (hospital, communications, transport) be protected? How much and which information should we share? What can be on the internet? Between the intelligence community and scientists information should be shared to improve quality of threat prediction. Also development of sensor systems for monitoring structures are stressed. Further research is required to prioritize and mitigate consequences. How do we plan ahead (societal preparedness). A multidisciplinary approach is crucial; preventive intervention to avoid psychological effects, even hysteria amplified by media/politics influence, but also modeling and data on sub-lethal effects (injuries impeding self-rescue and classification of urgency to apply medical aid) to plan more detailed emergency response.
- *Organization for Preparedness & Emergency Response*: The human being is central; education is crucial: education of first responders, and the people in general taking into account people's risk perception. Objectives of education are: recognizing the risk, getting trust in organizations and what action to pursue. People are more willing to change behavior it they feel being "at war" (solidarity). Needed is learning from past experiences, clear information on risk/threat and level of alertness and integration of resilience principles (redundancy, diversity, efficiency, autonomy, strength, integration, adaptability, collaboration) in various disciplines. For the (spatial) planning this means transparency in decision making, communications, building trust in institutions, role/sense of responsibility of actors. Research questions concern particularly how to

produce reliable information, to implement and realize, to institutionalize and obtain cooperation.

- *Materials & Structures*: Performance goals are safety of people, preservation of properties, mitigation of damages, restoration, reparability, stability and remote real time structural monitoring. Design parameters for extreme loading of structure by storm, earthquake, soil motion, explosive blast, impact, fire, extreme snowstorm and combined loading have to be formulated and standardized. Properties of building materials such as concrete, steel, wood, masonry, composites incl. plastics, glass and gypsum have to be characterized up to failure conditions under thermal (fire), dynamic and long term effects. The design approach needed is non-linear to cope with extreme static and dynamic loading conditions. Safety factors and failure limit state need to be discussed. As regards loading, on academic level much is known but translation to engineering level is required and embodied in new codes and standards. For materials specifications up to failure conditions under the various effects (thermal, impact, long term ageing) is needed. New fire protection technology and new materials with high specific strength are desirable. For the non-linear design approach new tools have to be developed. Finally existing infrastructures have to be assessed against the performance criteria and where needed being retrofitted.
- *Monitoring Structures* with sensors in a network can greatly help to detect slow deformations, cracks and other deficiencies, and to predict remaining resilience as to prevent disastrous collapse with people exposed. The networks created may also be used for detecting intrusion of persons and hazardous agents. Such monitoring will require advanced techniques of sensing, data collection and processing and information extraction. It is recommended to focus on:
  - Methods of estimation of completeness of data, irrespective of way of processing
  - Methods of data processing including approaches using fuzzy logic
  - Maintaining knowledge bases for Structural Health Monitoring
  - Advanced sensors for measurement of structural resilience

  - Wireless, remote and other advanced approaches to collecting information from sensor network or areas under monitoring
  - Globally integrated sensing systems for SHM
  - Sensor network robustness
  - Use for monitoring of SHM as much as possible existing security and communication systems.
- *Resilience and Economy*: In conclusion challenge to the community will be improving the resilience of cities to multi-hazard threats both by engineering measures and psychological preparedness resulting in an improved ability to cope with faults and failures. Apart from designing and introducing concrete measures economics will require to show pay-off of investments. This will demand the expression of resilience of complex systems in a quantitative way. To fulfill such requirement will be quite a challenge in itself.

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